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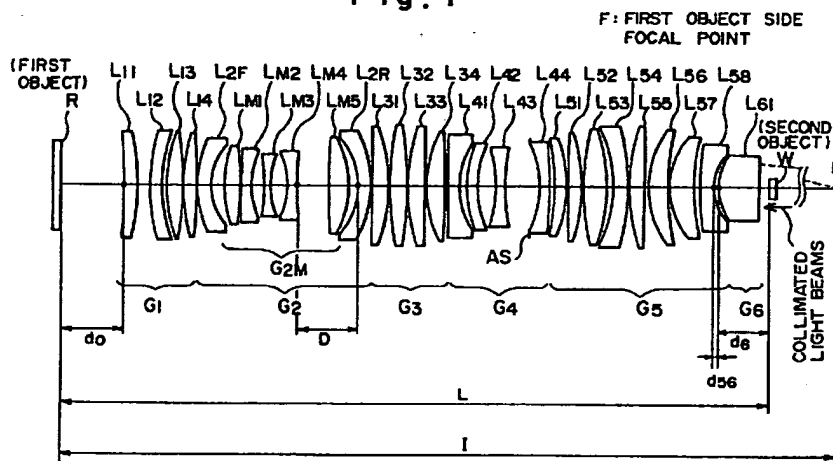
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## (54) Exposure apparatus

(57) A projection optical system of the present invention has a first lens group  $G_1$  being positive, a second lens group  $G_2$  being negative, a third lens group  $G_3$  being positive, a fourth lens group  $G_4$  being negative, a fifth lens group  $G_5$  being positive, and a sixth lens group  $G_6$  being positive in the named order from the object side, in which the second lens group  $G_2$  comprises an intermediate lens group  $G_{2M}$  between a negative front lens  $L_{2F}$  and a negative rear lens  $L_{2R}$  and in which the intermediate lens group  $G_{2M}$  is arranged to comprise at least

a first positive lens being positive, a second lens being negative, a third lens being negative, and a fourth lens being negative in the named order from the object side. The present invention involves findings of suitable focal length ranges for the first to the sixth lens groups  $G_1$  to  $G_6$  and an optimum range of an overall focal length of from the second negative lens to the fourth lens with respect to a focal length of the second lens group  $G_2$ .

Fig. 1



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## Description

BACKGROUND OF THE INVENTION5 Field of the invention

The present invention relates to an exposure apparatus having a projection optical system for projecting a pattern of a first object onto a photosensitive substrate etc. as a second object, and more particularly to a projection optical system suitably applicable to projection exposure of a pattern for semiconductor or liquid crystal formed on a reticle (mask) as the first object onto the substrate (semiconductor wafer, plate, etc.) as the second object.

Related background art

As the patterns of integrated circuits become finer and finer, the resolving power required for the exposure apparatus used in printing of wafer also becomes higher and higher. In addition to the improvement in resolving power, the projection optical systems of the exposure apparatus are required to decrease image stress.

Here, the image stress includes those due to bowing etc. of the printed wafer on the image side of projection optical system and those due to bowing etc. of the reticle with circuit pattern etc. written therein, on the object side of projection optical system, as well as distortion caused by the projection optical system.

20 With a recent further progress of fineness tendency of transfer patterns, demands to decrease the image stress are also becoming harder.

Then, in order to decrease effects of the wafer bowing on the image stress, the conventional technology has employed the so-called image-side telecentric optical system that located the exit pupil position at a farther point on the image side of projection optical system.

25 On the other hand, the image stress due to the bowing of reticle can also be reduced by employing a so-called object-side telecentric optical system that locates the entrance pupil position of projection optical system at a farther point from the object plane, and there are suggestions to locate the entrance pupil position of projection optical system at a relatively far position from the object plane as described. Examples of those suggestions are described for example in Japanese Laid-open Patent Applications No. 63-118115 and No. 5-173065 and U.S. Patent No. 5,260,832.

30 SUMMARY OF THE INVENTION

An object of the invention is to provide an exposure apparatus having a high-performance projection optical system which can correct the aberrations, particularly the distortion, very well even in the bitelecentric arrangement while keeping a relatively wide exposure area and a large numerical aperture.

To achieve the above object, the present invention involves an exposure apparatus having a high-performance projection optical system comprising a stage allowing a photosensitive substrate (for example, a semiconductor wafer coated with a photosensitive material such as a photoresist) to be held on a main surface thereof, an illumination optical system having a light source for emitting exposure light of a predetermined wavelength and transferring a predetermined pattern on a mask onto the substrate, and a projecting optical system for projecting an image of the mask, on the substrate surface. The above projecting optical system having for projecting an image of a first object (for example, a mask with a pattern such as an integrated circuit) onto a second object (for example, a photosensitive substrate).

As shown in Fig. 1, the projection optical system has a first lens group  $G_1$  with positive refracting power, a second lens group  $G_2$  with negative refracting power, a third lens group  $G_3$  with positive refracting power, a fourth lens group  $G_4$  with negative refracting power, a fifth lens group  $G_5$  with positive refracting power, and a sixth lens group  $G_6$  with positive refracting power in the named order from the side of the first object R, and the second lens group  $G_2$  further comprises a front lens  $L_{2F}$  placed as closest to the first object R and having negative refracting power with a concave surface to the second object W, a rear lens  $L_{2R}$  placed as closest to the second object and having negative refracting power with a concave surface to the first object R, and an intermediate lens group  $G_{2M}$  placed between the front lens  $L_{2F}$  in the second lens group  $G_2$  and the rear lens  $L_{2R}$  in the second lens group  $G_2$ . The intermediate lens group  $G_{2M}$  has a first lens  $L_{M1}$  with positive refracting power, a second lens  $L_{M2}$  with negative refracting power, a third lens  $L_{M3}$  with negative refracting power, and a fourth lens  $L_{M4}$  with negative refracting power in the named order from the side of the first object R.

First, the first lens group  $G_1$  with positive refracting power contributes mainly to a correction of distortion while maintaining telecentricity, and specifically, the first lens group  $G_1$  is arranged to generate a positive distortion to correct in a good balance negative distortions caused by the plurality of lens groups located on the second object side after the first lens group  $G_1$ . The second lens group  $G_2$  with negative refracting power and the fourth lens group  $G_4$  with negative refracting power contribute mainly to a correction of Petzval sum to make the image plane flat. The two lens groups of the second lens group  $G_2$  with negative refracting power and the third lens group  $G_3$  with positive refracting power form

an inverse telescopic system to contribute to guarantee of back focus (a distance from an optical surface such as a lens surface closest to the second object W in the projection optical system to the second object W) in the projection optical system. The fifth lens group  $G_5$  with positive refracting power and the sixth lens group  $G_6$  similarly with positive refracting power contribute mainly to suppressing generation of distortion and suppressing generation particularly of spherical aberration as much as possible in order to fully support high NA structure on the second object side.

Based on the above structure, the front lens  $L_{2F}$  placed as closest to the first object R in the second lens group  $G_2$  and having the negative refracting power with a concave surface to the second object W contributes to corrections of curvature of field and coma, and the rear lens  $L_{2R}$  placed as closest to the second object W in the second lens group  $G_2$  and having the negative refracting power with a concave surface to the first object R to corrections of curvature of field, coma, and astigmatism. In the intermediate lens group  $G_{2M}$  placed between the front lens  $L_{2F}$  and the rear lens  $L_{2R}$ , the first lens  $L_{M1}$  with positive refracting power contributes to a correction of negative distortions caused by the second to fourth lenses  $L_{M2}$ - $L_{M4}$  with negative refracting power greatly contributing to the correction of curvature of field.

In particular, in the above projecting optical system, the following conditions (1) to (5) are satisfied when a focal length of the first lens group  $G_1$  is  $f_1$ , a focal length of the second lens group  $G_2$  is  $f_2$ , a focal length of the third lens group  $G_3$  is  $f_3$ , a focal length of the fourth lens group  $G_4$  is  $f_4$ , a focal length of the fifth lens group  $G_5$  is  $f_5$ , a focal length of the sixth lens group  $G_6$  is  $f_6$ , an overall focal length of the second to the fourth lenses  $L_{M2}$ - $L_{M4}$  in the intermediate lens group  $G_{2M}$  in the second lens group  $G_2$  is  $f_n$ , and a distance from the first object R to the second object W is L:

$$0.1 < f_1/f_3 < 17 \quad (1)$$

$$0.1 < f_2/f_4 < 14 \quad (2)$$

$$0.01 < f_5/L < 0.9 \quad (3)$$

$$0.02 < f_6/L < 1.6 \quad (4)$$

$$0.01 < f_n/f_2 < 2.0. \quad (5)$$

The condition (1) defines an optimum ratio between the focal length  $f_1$  of the first lens group  $G_1$  with positive refracting power and the focal length  $f_3$  of the third lens group  $G_3$  with positive refracting power, which is an optimum refracting power (power) balance between the first lens group  $G_1$  and the third lens group  $G_3$ . This condition (1) is mainly for correcting the distortion in a good balance. Below the lower limit of this condition (1) a large negative distortion is produced because the refracting power of the third lens group  $G_3$  becomes relatively weak to the refracting power of the first lens group  $G_1$ . Above the upper limit of the condition (1) a large negative distortion is produced because the refracting power of the first lens group  $G_1$  becomes relatively weak to the refracting power of the third lens group  $G_3$ .

The condition (2) defines an optimum ratio between the focal length  $f_2$  of the second lens group  $G_2$  with negative refracting power and the focal length  $f_4$  of the fourth lens group  $G_4$  with negative refracting power, which is an optimum refracting power (power) balance between the second lens group  $G_2$  and the fourth lens group  $G_4$ . This condition (2) is mainly for keeping the Petzval sum small so as to correct the curvature of field well while securing a wide exposure field. Below the lower limit of the condition (2), a large positive Petzval sum appears because the refracting power of the fourth lens group  $G_4$  becomes relatively weak to the refracting power of the second lens group  $G_2$ . Above the upper limit of the condition (2) a large positive Petzval sum appears because the refracting power of the second lens group  $G_2$  becomes relatively weak to the refracting power of the fourth lens group  $G_4$ . In order to correct the Petzval sum in a better balance under a wide exposure field by making the refracting power of the fourth lens group  $G_4$  strong relative to the refracting power of the second lens group  $G_2$ , the lower limit of the above condition (2) is preferably set to 0.8, i.e.,  $0.8 < f_2/f_4$ .

The condition (3) defines an optimum ratio between the focal length  $f_5$  of the fifth lens group  $G_5$  with positive refracting power and the distance (object-image distance) L from the first object R (reticle etc.) and the second object W (wafer etc.). This condition (3) is for correcting the spherical aberration, distortion, and Petzval sum in a good balance while keeping a large numerical aperture. Below the lower limit of this condition (3) the refracting power of the fifth lens group  $G_5$  is too strong, so that this fifth lens group  $G_5$  generates not only a negative distortion but also a great negative spherical aberration. Above the upper limit of this condition (3) the refracting power of the fifth lens group  $G_5$  is too weak, so that the refracting power of the fourth lens group  $G_4$  with negative refracting power inevitably also becomes weak therewith, thereby resulting in failing to correct the Petzval sum well.

The condition (4) defines an optimum ratio between the focal length  $f_6$  of the sixth lens group  $G_6$  with positive refracting power and the distance (object-image distance) L from the first object R (reticle etc.) to the second object W (wafer etc.). This condition (4) is for suppressing generation of higher-order spherical aberrations and negative distortion while keeping a large numerical aperture. Below the lower limit of this condition (4) the sixth lens group  $G_6$  itself produces a large negative distortion; above the upper limit of this condition (4) higher-order spherical aberrations appear.

The condition (5) defines an optimum ratio between the overall focal length  $f_n$  of the second lens  $L_{M2}$  with negative refracting power to the fourth lens  $L_{M4}$  with negative refracting power in the intermediate lens group  $G_{2M}$  in the second lens group  $G_2$  and the focal length  $f_2$  of the second lens group  $G_2$ . It should be noted that the overall focal length  $f_n$ , stated herein, of the second lens  $L_{M2}$  with negative refracting power to the fourth lens  $L_{M4}$  with negative refracting power in the intermediate lens group  $G_{2M}$  in the second lens group  $G_2$  means not only an overall focal length of three lenses, i.e. the second lens  $L_{M2}$  to the fourth lens  $L_{M4}$ , but also an overall focal length of three or more lenses between the second lens  $L_{M2}$  and the fourth lens  $L_{M4}$  where there are a plurality of lenses between the second lens and the fourth lens.

This condition (5) is for keeping the Petzval sum small while suppressing generation of distortion. Below the lower limit of this condition (5), a great negative distortion appears because the overall refracting power becomes too strong, of the negative sublens group including at least three negative lenses of from the second negative lens  $L_{M2}$  to the fourth negative lens  $L_{M4}$  in the intermediate lens group  $G_{2M}$  in the second lens group  $G_2$ . In order to sufficiently correct the distortion and coma, the lower limit of the above condition (5) is preferably set to 0.1, i.e.,  $0.1 < f_n/f_2$ .

Above the upper limit of this condition (5) a great positive Petzval sum results because the refracting power of the negative sublens group including at least three negative lenses of from the second negative lens  $L_{M2}$  to the fourth negative lens  $L_{M4}$  in the intermediate lens group  $G_{2M}$  in the second lens group  $G_2$  becomes too weak. In addition, the refracting power of the third lens group  $G_3$  also becomes weak. Thus, it becomes difficult to construct the projection optical system in a compact arrangement. In order to achieve a sufficiently compact design while well correcting the Petzval sum, the upper limit of the above condition (5) is preferably set to 1.3, i.e.,  $f_n/f_2 < 1.3$ .

Further, the following condition (6) is preferably satisfied when the axial distance from the first object R to the first-object-side focal point F of the entire projection optical system is  $l$  and the distance from the first object R to the second object W is  $L$ .

$$1.0 < l/L \quad (6)$$

The condition (6) defines an optimum ratio between the axial distance  $l$  from the first object R to the first-object-side focal point F of the entire projection optical system and the distance (object-image distance)  $L$  from the first object R (reticle etc.) to the second object W (wafer etc.). Here, the first-object-side focal point F of the entire projection optical system means an intersecting point of outgoing light from the projection optical system with the optical axis after collimated light beams are let to enter the projection optical system on the second object side in the paraxial region with respect to the optical axis of the projection optical system and when the light beams in the paraxial region are outgoing from the projection optical system.

Below the lower limit of this condition (6) the first-object-side telecentricity of the projection optical system will become considerably destroyed, so that changes of magnification and distortion due to an axial deviation of the first object R will become large. As a result, it becomes difficult to faithfully project an image of the first object R at a desired magnification onto the second object W. In order to fully suppress the changes of magnification and distortion due to the axial deviation of the first object R, the lower limit of the above condition (6) is preferably set to 1.7, i.e.,  $1.7 < l/L$ . Further, in order to correct a spherical aberration and a distortion of the pupil both in a good balance while maintaining the compact design of the projection optical system, the upper limit of the above condition (6) is preferably set to 6.8, i.e.,  $l/L < 6.8$ .

Also, it is more preferable that the following condition (7) be satisfied when the focal length of the third lens  $L_{M3}$  with negative refracting power in the intermediate lens group  $G_{2M}$  in the second lens group  $G_2$  is  $f_{23}$  and the focal length of the fourth lens  $L_{M4}$  with negative refracting power in the intermediate lens group  $G_{2M}$  in the second lens group  $G_2$  is  $f_{24}$ .

$$0.07 < f_{24}/f_{23} < 7. \quad (7)$$

Below the lower limit of the condition (7) the refracting power of the fourth negative lens  $L_{M4}$  becomes strong relative to the refracting power of the third negative lens  $L_{M3}$ , so that the fourth negative lens  $L_{M4}$  generates a large coma and a large negative distortion. In order to correct the coma better while correcting the negative distortion, the lower limit of the above condition (7) is preferably set to 0.14, i.e.,  $0.14 < f_{24}/f_{23}$ . Above the upper limit of this condition (7) the refracting power of the third negative lens  $L_{M3}$  becomes relatively strong relative to the refracting power of the fourth negative lens  $L_{M4}$ , so that the third negative lens  $L_{M3}$  generates a large coma and a large negative distortion. In order to correct the negative distortion better while correcting the coma, the upper limit of the above condition (7) is preferably set to 3.5, i.e.,  $f_{24}/f_{23} < 3.5$ .

Further, it is more preferable that the following condition (8) be satisfied when the focal length of the second lens  $L_{M2}$  with negative refracting power in the intermediate lens group  $G_{2M}$  in the second lens group  $G_2$  is  $f_{22}$  and the focal length of the third lens  $L_{M3}$  with negative refracting power in the intermediate lens group  $G_{2M}$  in the second lens group  $G_2$  is  $f_{23}$ .

$$0.1 < f_{22}/f_{23} < 10 \quad (8)$$

Below the lower limit of the condition (8) the refracting power of the second negative lens  $L_{M2}$  becomes strong relative to the refracting power of the third negative lens  $L_{M3}$ , so that the second negative lens  $L_{M2}$  generates a large coma and a large negative distortion. In order to correct the negative distortion in a better balance, the lower limit of the above condition (8) is preferably set to 0.2, i.e.,  $0.2 < f_{22}/f_{23}$ . Above the upper limit of this condition (8) the refracting power of the third negative lens  $L_{M3}$  becomes strong relative to the refracting power of the second negative lens  $L_{M2}$ , so that the third negative lens  $L_{M3}$  generates a large coma and a large negative distortion. In order to correct the negative distortion in a better balance while well correcting the coma, the upper limit of the above condition (8) is preferably set to 5, i.e.,  $f_{22}/f_{23} < 5$ .

Also, it is more desirable that the following condition (9) be satisfied when the axial distance from the second-object-side lens surface of the fourth lens  $L_{M4}$  with negative refracting power in the intermediate lens group  $G_{2M}$  in the second lens group  $G_2$  to the first-object-side lens surface of the rear lens  $L_{2R}$  in the second lens group  $G_2$  is  $D$  and the distance from the first object  $R$  to the second object  $W$  is  $L$ :

$$0.05 < D/L < 0.4. \quad (9)$$

Below the lower limit of the condition (9) it becomes difficult not only to secure a sufficient back focus on the second object side but also to correct the Petzval sum well. Above the upper limit of the condition (9) a large coma and a large negative distortion appear. Further, for example, in order to avoid mechanical interference between a reticle stage for holding the reticle as the first object  $R$  and the first lens group  $G_1$ , there are cases that it is preferable to secure a sufficient space between the first object  $R$  and the first lens group  $G_1$ , but there is a problem that to secure the sufficient space will become difficult above the upper limit of the condition (9).

Also, the fourth lens group  $G_4$  preferably satisfies the following condition when the focal length of the fourth lens group  $G_4$  is  $f_4$  and the distance from the first object  $R$  to the second object  $W$  is  $L$ .

$$-0.098 < f_4/L < -0.005 \quad (10)$$

Below the lower limit of the condition (10) the correction of spherical aberration becomes difficult, which is not preferable. Also, above the upper limit of the condition (10), the coma appears, which is not preferable. In order to well correct the spherical aberration and Petzval sum, the lower limit of the condition (10) is preferably set to -0.078, i.e.,  $-0.078 < f_4/L$ , and further, in order to suppress generation of coma, the upper limit of the condition (10) is preferably set to -0.047, i.e.,  $f_4/L < -0.047$ .

Further, the second lens group  $G_2$  preferably satisfies the following condition when the focal length of the second lens group  $G_2$  is  $f_2$  and the distance from the first object  $R$  to the second object  $W$  is  $L$ .

$$-0.8 < f_2/L < -0.050 \quad (11)$$

Here, below the lower limit of the condition (11), a positive Petzval sum results, which is not preferable. Also, above the upper limit of the condition (11), a negative distortion appears, which is not preferable. In order to better correct the Petzval sum, the lower limit of the condition (11) is preferably set to -0.16, i.e.,  $-0.16 < f_2/L$ , and in order to better correct the negative distortion and coma, the upper limit of the condition (11) is preferably set to -0.0710, i.e.,  $f_2/L < -0.0710$ .

In order to well correct mainly the third-order spherical aberration, it is more desirable that the fifth lens group  $G_5$  with positive refracting power have the negative meniscus lens  $L_{54}$ , and the positive lens  $L_{53}$  placed adjacent to the concave surface of the negative meniscus lens  $L_{54}$  and having a convex surface opposed to the concave surface of the negative meniscus lens  $L_{54}$  and that the following condition (12) be satisfied when the radius of curvature of the concave surface in the negative meniscus lens  $L_{54}$  in the fifth lens group  $G_5$  is  $r_{5n}$  and the radius of curvature of the convex surface opposed to the concave surface of the negative meniscus lens  $L_{54}$  in the positive lens  $L_{53}$  set adjacent to the concave surface of the negative meniscus lens  $L_{54}$  in the fifth lens group  $G_5$  is  $r_{5p}$ .

$$0 < (r_{5p} - r_{5n})/(r_{5p} + r_{5n}) < 1 \quad (12)$$

Below the lower limit of the condition (12), correction of the third-order spherical aberration becomes insufficient; conversely, above the upper limit of the condition (12), the correction of the third-order spherical aberration becomes excessive, which is not preferable. Here, in order to correct the third-order spherical aberration better, the lower limit of the condition (12) is more preferably set to 0.01, i.e.,  $0.01 < (r_{5p} - r_{5n})/(r_{5p} + r_{5n})$  and the upper limit of the condition (12) is more preferably set to 0.7, i.e.,  $(r_{5p} - r_{5n})/(r_{5p} + r_{5n}) < 0.7$ .

Here, it is preferred that the negative meniscus lens and the positive lens adjacent to the concave surface of the negative meniscus lens be set between the at least one positive lens in the fifth lens group  $G_5$  and the at least one positive lens in the fifth lens group  $G_5$ . For example, a set of the negative meniscus lens  $L_{54}$  and the positive lens  $L_{53}$

is placed between the positive lenses  $L_{52}$  and  $L_{55}$ . This arrangement can suppress generation of the higher-order spherical aberrations which tend to appear with an increase in NA.

Also, it is more desirable that the fourth lens group  $G_4$  with negative refracting power have the front lens  $L_{41}$  placed as closest to the first object R and having the negative refracting power with a concave surface to the second object W, the rear lens  $L_{44}$  placed as closest to the second object W and having the negative refracting power with a concave surface to the first object R, and at least one negative lens placed between the front lens  $L_{41}$  in the fourth lens group  $G_4$  and the rear lens  $L_{44}$  in the fourth lens group  $G_4$  and that the following condition (13) be satisfied when a radius of curvature on the first object side in the rear lens  $L_{44}$  placed as closest to the second object W in the fourth lens group  $G_4$  is  $r_{4F}$  and a radius of curvature on the second object side in the rear lens  $L_{44}$  placed as closest to the second object W in the fourth lens group  $G_4$  is  $r_{4R}$ .

$$-1.00 \leq (r_{4F} - r_{4R}) / (r_{4F} + r_{4R}) < 0 \quad (13)$$

Below the lower limit of the condition (13), the rear negative lens  $L_{44}$  located closest to the second object W in the fourth lens group  $G_4$  becomes of a double-concave shape which generates higher-order spherical aberrations; conversely, above the upper limit of the condition (13), the rear negative lens  $L_{44}$  located closest to the second object W in the fourth lens group  $G_4$  will have positive refracting power, which will make the correction of Petzval sum more difficult.

Further, it is desirable that the fifth lens group  $G_5$  have the negative lens  $L_{58}$  with a concave surface to the second object W, on the most second object side thereof. This enables the negative lens  $L_{58}$  located closest to the second object W in the fifth lens group  $G_5$  to generate a positive distortion and a negative Petzval sum, which can cancel a negative distortion and a positive Petzval sum generated by the positive lenses in the fifth lens group  $G_5$ .

In this case, in order to suppress the negative distortion without generating the higher-order spherical aberrations in the lens  $L_{61}$  located closest to the first object R in the sixth lens group  $G_6$ , it is desirable that the lens surface closest to the first object R have a shape with a convex surface to the first object R and that the following condition be satisfied when a radius of curvature on the second object side, of the negative lens  $L_{58}$  placed as closest to the second object W in the fifth lens group  $G_5$  is  $r_{5R}$  and a radius of curvature on the first object side, of the lens  $L_{61}$  placed as closest to the first object R in the sixth lens group  $G_6$  is  $r_{6F}$ .

$$-0.90 < (r_{5R} - r_{6F}) / (r_{5R} + r_{6F}) < -0.001 \quad (14)$$

This condition (14) defines an optimum shape of a gas lens formed between the fifth lens group  $G_5$  and the sixth lens group  $G_6$ . Below the lower limit of this condition (14) a curvature of the second-object-side concave surface of the negative lens  $L_{58}$  located closest to the second object W in the fifth lens group  $G_5$  becomes too strong, thereby generating higher-order comas. Above the upper limit of this condition (14) refracting power of the gas lens itself formed between the fifth lens group  $G_5$  and the sixth lens group  $G_6$  becomes weak, so that a quantity of the positive distortion generated by this gas lens becomes small, which makes it difficult to well correct a negative distortion generated by the positive lenses in the fifth lens group  $G_5$ . In order to fully suppress the generation of higher-order comas, the lower limit of the above condition (14) is preferably set to -0.30, i.e.,  $-0.30 < (r_{5R} - r_{6F}) / (r_{5R} + r_{6F})$ .

Also, it is further preferable that the following condition be satisfied when a lens group separation between the fifth lens group  $G_5$  and the sixth lens group  $G_6$  is  $d_{56}$  and the distance from the first object R to the second object W is L.

$$d_{56} / L < 0.017 \quad (15)$$

Above the upper limit of this condition (15), the lens group separation between the fifth lens group  $G_5$  and the sixth lens group  $G_6$  becomes too large, so that a quantity of the positive distortion generated becomes small. As a result, it becomes difficult to correct the negative distortion generated by the positive lens in the fifth lens group  $G_5$  in a good balance.

Also, it is more preferable that the following condition be satisfied when a radius of curvature of the lens surface closest to the first object R in the sixth lens group  $G_6$  is  $r_{6F}$  and an axial distance from the lens surface closest to the first object R in the sixth lens group  $G_6$  to the second object W is  $d_6$ .

$$0.50 < d_6 / r_{6F} < 1.50 \quad (16)$$

Below the lower limit of this condition (16), the positive refracting power of the lens surface closest to the first object R in the sixth lens group  $G_6$  becomes too strong, so that a large negative distortion and a large coma are generated. Above the upper limit of this condition (16), the positive refracting power of the lens surface closest to the first object R in the sixth lens group  $G_6$  becomes too weak, thus generating a large coma. In order to further suppress the generation of coma, the lower limit of the condition (16) is preferably set to 0.84, i.e.,  $0.84 < d_6 / r_{6F}$ .

It is desirable that the following condition (17) be satisfied when the radius of curvature on the first object side in the negative lens  $L_{58}$  located closest to the second object W in the fifth lens group  $G_5$  is  $r_{5F}$  and the radius of curvature on the second object side in the negative lens  $L_{58}$  located closest to the second object W in the fifth lens group  $G_5$  is  $r_{5R}$ .

$$0.30 < (r_{5F} - r_{5R}) / (r_{5F} + r_{5R}) < 1.28 \quad (17)$$

Below the lower limit of this condition (17), it becomes difficult to correct both the Petzval sum and the coma; above the upper limit of this condition (17), large higher-order comas appear, which is not preferable. In order to further prevent the generation of higher-order comas, the upper limit of the condition (17) is preferably set to 0.93, i.e.,  $(r_{5F} - r_{5R}) / (r_{5F} + r_{5R}) < 0.93$ .

Further, it is desirable that the second-object-side lens surface of the first lens  $L_{M1}$  with positive refracting power in the intermediate lens group  $G_{2M}$  in the second lens group  $G_2$  be of a lens shape with a convex surface to the second object W, and in this case, it is more preferable that the following condition (18) be satisfied when the refracting power on the second-object-side lens surface of the first positive lens  $L_{M1}$  in the intermediate lens group  $G_{2M}$  in the second lens group  $G_2$  is  $\Phi_{21}$  and the distance from the first object R to the second object W is L.

$$0.54 < 1 / (\Phi_{21} \cdot L) < 10 \quad (18)$$

The refracting power of the second-object-side lens surface, stated herein, of the first lens  $L_{M1}$  with positive refracting power in the intermediate lens group  $G_{2M}$  is given by the following formula when a refractive index of a medium for the first lens  $L_{M1}$  is  $n_1$ , a refracting index of a medium in contact with the second-object-side lens surface of the first lens  $L_{M1}$  is  $n_2$ , and a radius of curvature of the second-object-side lens surface of the first lens is  $r_{21}$ .

$$\Phi_{21} = (n_2 - n_1) / r_{21}$$

Below the lower limit of the condition (18), higher-order distortions appear; conversely, above the upper limit of the condition (18), it becomes necessary to correct the distortion more excessively by the first lens group  $G_1$ , which generates the spherical aberration of the pupil, thus being not preferable.

Further, it is more preferable that the following condition (19) be satisfied when the focal length of the first lens  $L_{M1}$  with positive refracting power in the intermediate lens group  $G_{2M}$  in the second lens group  $G_2$  is  $f_{21}$  and the distance from the first object R to the second object W is L.

$$0.230 < f_{21} / L < 0.40 \quad (19)$$

Below the lower limit of the condition (19), a positive distortion appears; above the upper limit of the condition (19), a negative distortion appears, thus not preferable.

Also, the front lens  $L_{2F}$  and rear lens  $L_{2R}$  in the second lens group  $G_2$  preferably satisfy the following condition when the focal length of the front lens  $L_{2F}$  placed as closest to the first object R in the second lens group  $G_2$  and having the negative refracting power with a concave surface to the second object W is  $f_{2F}$  and the focal length of the rear lens  $L_{2R}$  placed as closest to the second object W in the second lens group  $G_2$  and having the negative refracting power with a concave surface to the first object R is  $f_{2R}$ .

$$0 \leq f_{2F} / f_{2R} < 18 \quad (20)$$

The condition (20) defines an optimum ratio between the focal length  $f_{2R}$  of the rear lens  $L_{2R}$  in the second lens group  $G_2$  and the focal length  $f_{2F}$  of the front lens  $L_{2F}$  in the second lens group  $G_2$ . Below the lower limit and above the upper limit of this condition (20), a balance is destroyed for refracting power of the first lens group  $G_1$  or the third lens group  $G_3$ , which makes it difficult to correct the distortion well or to correct the Petzval sum and the astigmatism simultaneously well.

The following specific arrangements are desirable to provide the above respective lens groups with sufficient aberration control functions.

First, in order to provide the first lens group  $G_1$  with a function to suppress generation of higher-order distortions and spherical aberration of the pupil, the first lens group  $G_1$  preferably has at least two positive lenses; in order to provide the third lens group  $G_3$  with a function to suppress degradation of the spherical aberration and the Petzval sum, the third lens group  $G_3$  preferably has at least three positive lenses; further, in order to provide the fourth lens group  $G_4$  with a function to suppress the generation of coma while correcting the Petzval sum, the fourth lens group  $G_4$  preferably has at least three negative lenses. Further, in order to provide the fifth lens group  $G_5$  with a function to suppress generation of the negative distortion and the spherical aberration, the fifth lens group  $G_5$  preferably has at least five positive lenses; further, in order to provide the fifth lens group  $G_5$  with a function to correct the negative distortion and the Petzval sum,

the fifth lens group  $G_5$  preferably has at least one negative lens. Also, in order to provide the sixth lens group  $G_6$  with a function to converge light on the second object  $W$  without generating a large spherical aberration, the sixth lens group  $G_6$  preferably has at least one positive lens.

In addition, in order to correct the Petzval sum better, the intermediate lens group  $G_{2M}$  in the second lens group  $G_2$  preferably has negative refracting power.

In order to provide the sixth lens group  $G_6$  with a function to further suppress the generation of the negative distortion, the sixth lens group  $G_6$  is preferably constructed of three or less lenses having at least one surface satisfying the following condition (21).

$$1/|\Phi L| < 20 \quad (21)$$

where  $\Phi$ : refracting power of the lens surface;

$L$ : object-image distance from the first object  $R$  to the second object  $W$ .

The refracting power of the lens surface stated herein is given by the following formula when the radius of curvature of the lens surface is  $r$ , a refracting index of a medium on the first object side, of the lens surface is  $n_1$ , and a medium on the second object side, of the lens surface is  $n_2$ .

$$\Phi = (n_2 - n_1)/r$$

Here, if there are four or more lenses having the lens surface satisfying this condition (21), the number of lens surfaces with some curvature, located near the second object  $W$ , becomes increased, which generates the distortion, thus not preferable.

The present invention will become more fully understood from the detailed description given hereinbelow and the accompanying drawings which are given by way of illustration only, and thus are not to be considered as limiting the present invention.

Further scope of applicability of the present invention will become apparent from the detailed description given hereinafter. However, it should be understood that the detailed description and specific examples, while indicating preferred embodiments of the invention, are given by way of illustration only, since various changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art from this detailed description.

### BRIEF DESCRIPTION OF THE DRAWINGS

- Fig. 1 is a drawing to show parameters defined in embodiments of the present invention.  
 Fig. 2 is a drawing to show schematic structure of an exposure apparatus according to the present invention.  
 Fig. 3 is a lens makeup diagram in the first embodiment according to the present invention.  
 Fig. 4 is a lens makeup diagram in the second embodiment according to the present invention.  
 Fig. 5 is a lens makeup diagram in the third embodiment according to the present invention.  
 Fig. 6 is a lens makeup diagram in the fourth embodiment according to the present invention.  
 Fig. 7 is a lens makeup diagram in the fifth embodiment according to the present invention.  
 Fig. 8 is a lens makeup diagram in the sixth embodiment according to the present invention.  
 Fig. 9 is various aberration diagrams in the first embodiment according to the present invention.  
 Fig. 10 is various aberration diagrams in the second embodiment according to the present invention.  
 Fig. 11 is various aberration diagrams in the third embodiment according to the present invention.  
 Fig. 12 is various aberration diagrams in the fourth embodiment according to the present invention.  
 Fig. 13 is various aberration diagrams in the fifth embodiment according to the present invention.  
 Fig. 14 is various aberration diagrams in the sixth embodiment according to the present invention.

### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The embodiments according to the present invention will be described in detail in the following. An exposure apparatus of the invention comprises a projection optical system as shown in Fig. 2.

First, briefly describing Fig. 2, a reticle  $R$  (first object) is placed as a mask on which a predetermined circuit pattern 101 is formed, on the object plane of a projection optical system  $PL$  and a wafer  $W$  (second object) as a photosensitive substrate on the image plane of the projection optical system  $PL$ , as shown. The reticle  $R$  is held on a reticle stage  $RS$  while the wafer  $W$  on a wafer stage  $WS$ . The photosensitive substrate comprises the wafer  $W$  and a photosensitive layer 100 made of a material as a photoresistor. Further, an illumination optical system  $IS$ , which has a light source 102 for emitting exposure light of a predetermined wavelength, for uniformly illuminating the reticle  $R$  is set above the reticle  $R$ .

In the above arrangement, light supplied from the illumination optical system  $IS$  illuminates the reticle  $R$  to form an image of a light source in the illumination optical apparatus  $IS$  at the pupil position (or a position of aperture stop  $AS$ ) of



the projection optical system PL, thus achieving the so-called Köhler illumination. Then, through the projection optical system PL, a pattern image of the thus Köhler-illuminated reticle R is projected (or transferred) onto the wafer W through the photosensitive layer 100 by the projection optical system PL. The techniques relating to an exposure apparatus of the present invention are described for example in U.S. Patents No. 5,194,893, No. 5,097,291 and No. 5,245,384 and U.S. Patent Applications No. 299,305, No. 255,927 and No. 226,327.

The present embodiment shows an example of projection optical system where the light source 102 inside the illumination optical system IS is an excimer laser supplying light with exposure wavelength  $\lambda$  of 248.4 nm, and Fig. 3 to Fig. 8 are lens makeup diagrams of projection optical systems in the first to sixth embodiments according to the present invention.

As shown in Fig. 3 to Fig. 8, a projection optical system in each embodiment has a first lens group  $G_1$  with positive refracting power, a second lens group  $G_2$  with negative refracting power, a third lens group  $G_3$  with positive refracting power, a fourth lens group  $G_4$  with negative refracting power, a fifth lens group  $G_5$  with positive refracting power, and a sixth lens group  $G_6$  with positive refracting power in the named order from the side of reticle R as the first object, which is approximately telecentric on the object side (or on the reticle R side) and on the image side (or on the wafer W side) and which has a reduction magnification.

The projection optical systems of the respective embodiments shown in Fig. 3 to Fig. 8 are arranged so that the object-image distance (a distance from the object plane to the image plane or a distance from the reticle R to the wafer W)  $L$  is 1200, the image-side numerical aperture NA is 0.55, the projection magnification  $B$  is 5:1, and the diameter of the exposure area on the wafer W is 31.2. In the explanation of embodiments of the present invention, the image plane means a main surface of the wafer W, and the object plane means a surface of the reticle R.

Specifically describing the lens makeup of the first embodiment, as shown in Fig. 3, first, the first lens group  $G_1$  has a positive lens  $L_{11}$  with a convex surface to the image (positive meniscus lens), a negative lens  $L_{12}$  of a meniscus shape with a convex surface to the object, and two positive lenses ( $L_{13}$ ,  $L_{14}$ ) of a double-convex shape in the named order from the object side.

Next, the second lens group  $G_2$  is composed of a negative meniscus lens (front lens)  $L_{2F}$  placed as closest to the object with a concave surface to the image, a negative meniscus lens (rear lens)  $L_{2R}$  placed closest to the image with a concave surface to the object, and an intermediate lens group  $G_{2M}$  placed between the negative meniscus lens  $L_{2F}$  located closest to the object in the second lens group  $G_2$  and the negative meniscus lens  $L_{2R}$  located closest to the image in the second lens group  $G_2$ , and having negative refracting power.

The intermediate lens group  $G_{2M}$  is composed of a positive lens (first lens)  $L_{M1}$  of a double-convex shape, a negative lens (second lens)  $L_{M2}$  with a surface of a greater curvature to the image, a negative lens (third lens)  $L_{M3}$  of a double-concave shape, a negative lens (fourth lens)  $L_{M4}$  with a surface of a greater curvature to the object, and a positive lens (fifth lens)  $L_{M5}$  with a surface of a greater curvature to the image in the named order from the object side.

Further, the third lens group  $G_3$  is composed of a positive lens (positive meniscus lens)  $L_{31}$  with a surface of a greater curvature to the image, a positive lens  $L_{32}$  of a double-convex shape, a positive lens (a positive lens of a double-convex shape)  $L_{33}$  with a convex surface to the object, and a positive lens  $L_{34}$  with a surface of a greater curvature to the object, and the fourth lens group  $G_4$  is composed of a negative lens (negative meniscus lens)  $L_{41}$  with a concave surface to the image, a negative meniscus lens  $L_{42}$  with a concave surface to the image, a negative lens  $L_{43}$  of a double-concave surface, and a negative meniscus lens  $L_{44}$  with a concave surface to the object.

Here, an aperture stop AS is set in an optical path between the image-side concave surface of the negative lens  $L_{41}$  in the fourth lens group  $G_4$  and the object-side concave surface of the negative meniscus lens  $L_{44}$ .

The fifth lens group  $G_5$  is composed of a positive meniscus lens  $L_{51}$  with a convex surface to the image, a positive lens with a surface of a greater curvature to the image (a positive lens of a double-convex shape)  $L_{52}$ , a positive lens  $L_{53}$  of a double-convex shape, a negative meniscus lens  $L_{54}$  with a concave surface to the object, a positive lens  $L_{55}$  with a surface of a greater curvature to the object, a positive meniscus lens  $L_{56}$  with a convex surface to the object, a positive lens with a surface of a greater curvature to the object (positive meniscus lens)  $L_{57}$ , and a negative lens with a concave surface to the image (negative meniscus lens)  $L_{58}$ , and the sixth lens group  $G_6$  is composed only of a thick-wall positive lens  $L_{61}$  with a convex surface to the object.

Here, because the first lens group  $G_1$  in the first embodiment is so arranged that the image-side lens surface of the negative lens  $L_{12}$  of the meniscus shape with its convex surface to the object and the object-side lens surface of the positive lens  $L_{13}$  of double-convex shape have nearly equal curvatures and are arranged as relatively close to each other, these two lens surfaces correct the higher-order distortions.

In the present embodiment, because the front lens  $L_{2F}$  with negative refracting power, placed closest to the object in the second lens group  $G_2$ , is of the meniscus shape with a concave surface to the image, the generation of coma can be reduced; because the first lens  $L_{M1}$  with positive refracting power in the second lens group  $G_{2M}$  is of the double-convex shape with a convex surface to the image and another convex surface to the object, the generation of spherical aberration of the pupil can be suppressed. Further, because the fifth lens  $L_{M5}$  with positive refracting power in the intermediate lens group  $G_{2M}$  has the convex surface opposed to the concave surface of the rear lens  $L_{2R}$  with negative refracting power placed on the image side thereof, the astigmatism can be corrected.

Since the fourth lens group  $G_4$  is so arranged that the negative lens  $L_{41}$  with its concave surface to the image is placed on the object side of the negative lens (negative lens of double-concave shape)  $L_{43}$  and that the negative meniscus lens  $L_{44}$  with its concave surface to the object is placed on the image side of the negative lens (negative lens of double-concave shape)  $L_{43}$ , the Petzval sum can be corrected while suppressing the generation of coma.

The present embodiment is so arranged that the aperture stop AS is placed between the image-side concave surface of the negative lens  $L_{41}$  and the object-side concave surface of the negative meniscus lens  $L_{44}$  in the fourth lens group  $G_4$  whereby the lens groups of from the third lens group  $G_3$  to the sixth lens group  $G_6$  can be arranged on either side of the aperture stop AS with some reduction magnification and without destroying the symmetry so much, which can suppress generation of asymmetric aberrations, specifically generation of coma or distortion.

Since the positive lens  $L_{53}$  in the fifth lens group  $G_5$  is of the double-convex shape where its convex surface is opposed to the negative meniscus lens  $L_{54}$  and the other lens surface opposite to the negative meniscus lens  $L_{54}$  is also a convex surface, the generation of higher-order spherical aberrations with an increase in NA can be suppressed.

The specific lens makeup of the projection optical system in the second embodiment as shown in Fig. 4 is similar to that of the first embodiment shown in Fig. 3 and described above but different in that the fourth lens group  $G_4$  is composed of a negative lens with a concave surface to the image (negative lens of a plano-concave shape)  $L_{41}$ , a negative meniscus lens  $L_{42}$  with a concave surface to the image, a negative lens  $L_{43}$  of a double-concave shape, and a negative meniscus lens  $L_{44}$  with a concave surface to the object and in that the sixth lens group  $G_6$  is composed of a positive lens with a convex surface to the object (positive meniscus lens)  $L_{61}$ , and a positive lens with a convex surface to the object (positive meniscus lens)  $L_{62}$ .

Also in the second embodiment, the image-side lens surface of the negative meniscus lens  $L_{12}$  with its convex surface to the object and the object-side lens surface of the positive lens  $L_{13}$  of double-convex shape correct the higher-order distortions, similarly as in the above first embodiment. Further, the sixth lens group  $G_6$  is preferably composed of a less number of constituent lenses in order to suppress a distortion generated by the sixth lens group  $G_6$ , but if it is difficult to produce a thick lens the sixth lens group  $G_6$  may be composed of two lenses as in the present embodiment. As for the other lens groups (the second lens group  $G_2$  to the fifth lens group  $G_5$ ) in the second embodiment, the same functions as in the first embodiment are achieved thereby.

The specific lens makeup of the projection optical system of the third embodiment as shown in Fig. 5 is similar to that of the first embodiment shown in Fig. 3 and described previously, but different in that the first lens group  $G_1$  is composed of a positive lens with a convex surface to the image (positive lens of double-convex shape)  $L_{11}$ , a positive lens with a convex surface to the image (positive lens of double-convex shape)  $L_{12}$ , a negative meniscus lens  $L_{13}$  with a concave surface to the object, and a positive lens  $L_{14}$  of double-convex shape in the named order from the object side and in that the third lens group  $G_3$  is composed of a positive lens with a surface of a greater curvature to the image (positive meniscus lens)  $L_{31}$ , a positive lens  $L_{32}$  of double-convex shape, a positive lens with a surface of a greater curvature to the object (positive lens of double-convex shape)  $L_{33}$ , and a positive lens with a convex surface to the object (positive meniscus lens)  $L_{34}$ .

In the third embodiment, the image-side lens surface of the positive lens  $L_{12}$  with its convex surface to the image and the object-side lens surface of the negative meniscus lens  $L_{13}$  with its concave surface to the object correct the higher-order distortions. As for the other lens groups (the second lens group  $G_2$ , and the fourth lens group  $G_4$  to the sixth lens group  $G_6$ ) in the third embodiment, the same functions as in the first embodiment are achieved thereby.

The specific lens makeup of the projection optical system of the fourth embodiment as shown in Fig. 6 is similar to that of the third embodiment shown in Fig. 5 and described above, but different in that the third lens group  $G_3$  is composed of a positive lens with a surface of a greater curvature to the image side (positive meniscus lens)  $L_{31}$ , a positive lens  $L_{32}$  of double-convex shape, a positive lens with a convex surface to the object (positive lens of double-convex shape)  $L_{33}$ , and a positive lens with a surface of a greater curvature to the object (positive lens of double-convex shape)  $L_{34}$  and in that the fourth lens group  $G_4$  is composed of a negative lens with a concave surface to the image (negative lens of double-concave shape)  $L_{41}$ , a negative meniscus lens  $L_{42}$  with a concave surface to the image, a negative lens  $L_{43}$  of double-concave shape, and a negative meniscus lens  $L_{44}$  with a concave surface to the object. The present embodiment is also different in that the sixth lens group  $G_6$  is composed of a positive lens with a convex surface to the object (positive meniscus lens)  $L_{61}$  and a positive lens with a convex surface to the object (positive meniscus lens)  $L_{62}$ .

The first lens group  $G_1$  in the fourth embodiment achieves the same functions as in the third embodiment described previously, the second lens group  $G_2$  to the fifth lens group  $G_5$  do the same functions as in the first embodiment, and the sixth lens group  $G_6$  does the same functions as in the second embodiment.

The specific lens makeup of the projection optical system of the fifth embodiment shown in Fig. 7 is similar to that of the first embodiment shown in Fig. 3 and described previously, but different in that the first lens group  $G_1$  is composed of a positive lens with a convex surface to the image (positive lens of double-convex shape)  $L_{11}$ , a negative lens with a concave surface to the image (negative lens of double-concave shape)  $L_{12}$  and two positive lenses ( $L_{13}$ ,  $L_{14}$ ) of double-convex shape in the named order from the object side. It is also different in that the third lens group  $G_3$  is composed of a positive lens with a surface of a greater curvature to the image (positive meniscus lens)  $L_{31}$ , a positive lens  $L_{32}$  of double-convex shape, a positive lens with a convex surface to the object (positive meniscus lens)  $L_{33}$ , and a positive

lens with a surface of a greater curvature to the object (positive lens of double-convex shape)  $L_{34}$ . It is also different from the lens makeup of the first embodiment in that the fourth lens group  $G_4$  is composed of a negative lens with a concave surface to the image (negative lens of double-concave shape)  $L_{41}$ , a negative meniscus lens  $L_{42}$  with a concave surface to the image, a negative lens  $L_{43}$  of double-concave shape, and a negative meniscus lens  $L_{44}$  with a concave surface to the object. It is further different in that the fifth lens group  $G_5$  is composed of a positive meniscus lens  $L_{51}$  with a convex surface to the image, a positive lens with a surface of a greater curvature to the image (positive meniscus lens)  $L_{52}$ , a positive lens  $L_{53}$  of double-convex shape, a negative meniscus lens  $L_{54}$  with a concave surface to the object, a positive lens with a surface of a greater curvature to the object (positive meniscus lens)  $L_{55}$ , a positive meniscus lens  $L_{56}$  with a convex surface to the object, a positive lens with a surface of a greater curvature to the object (positive meniscus lens)  $L_{57}$ , and a negative lens with a concave surface to the image (negative meniscus lens)  $L_{58}$ .

In the fifth embodiment the higher-order distortions are corrected by a pair of the image-side convex surface of the positive lens  $L_{11}$  and the object-side concave surface of the negative lens  $L_{12}$  and a pair of the image-side concave surface of the negative lens  $L_{12}$  and the object-side convex surface of the positive lens  $L_{13}$ . As for the other lens groups (the second to the fifth lens groups  $G_2$  to  $G_5$ ) in the fifth embodiment, the same functions as in the first embodiment are achieved thereby.

The sixth embodiment shown in Fig. 8 has the same lens makeup as that of the fifth embodiment as described above, and achieves the substantially same functions as in the fifth embodiment.

Now, Table 1 to Table 12 listed below indicate values of specifications and numerical values corresponding to the conditions in the respective embodiments according to the present invention.

In the tables, left end numerals represent lens surfaces located in the named order from the object side (reticle side),  $r$  curvature radii of lens surfaces,  $d$  lens surface separations,  $n$  refractive indices of synthetic quartz  $\text{SiO}_2$  for the exposure wavelength  $\lambda$  of 248.4 nm,  $d_0$  a distance from the first object (reticle) to the lens surface (first lens surface) closest to the object (reticle) in the first lens group  $G_1$ ,  $B_f$  a distance from the lens surface closest to the image (wafer) in the sixth lens group  $G_6$  to the image plane (wafer surface),  $B$  a projection magnification of the projection optical system,  $NA$  the image-side numerical aperture of the projection optical system,  $L$  the object-image distance from the object plane (reticle surface) to the image plane (wafer surface),  $l$  the axial distance from the first object (reticle) to the first-object-side focal point of the entire projection optical system (where the first-object-side focal point of the entire projection optical system means an intersecting point of exit light with the optical axis after collimated light beams in the paraxial region with respect to the optical axis of the projection optical system are let to enter the projection optical system on the second object side and when the light beams in the paraxial region are outgoing from the projection optical system),  $f_1$  the focal length of the first lens group  $G_1$ ,  $f_2$  the focal length of the second lens group  $G_2$ ,  $f_3$  the focal length of the third lens group  $G_3$ ,  $f_4$  the focal length of the fourth lens group  $G_4$ ,  $f_5$  the focal length of the fifth lens group  $G_5$ ,  $f_6$  the focal length of the sixth lens group  $G_6$ ,  $f_n$  the overall focal length of from the second lens to the fourth lens,  $f_{2F}$  the focal length of the front lens placed closest to the first object in the second lens group and having negative refracting power with its concave surface to the second object,  $f_{2R}$  the focal length of the rear lens placed closest to the second object in the second lens group and having negative refracting power with its concave surface to the first object,  $f_{21}$  the focal length of the first lens with positive refracting power in the intermediate lens group in the second lens group,  $f_{22}$  the focal length of the second lens with negative refracting power in the second lens group,  $f_{23}$  the focal length of the third lens with negative refracting power in the second lens group,  $f_{24}$  the focal length of the fourth lens with negative refracting power in the second lens group,  $\Phi_{21}$  the refracting power of the second-object-side lens surface of the first lens with positive refracting power in the intermediate lens group  $G_{21}$  in the second lens group,  $D$  the axial distance from the second-object-side lens surface of the fourth lens in the intermediate lens group in the second lens group to the first-object-side lens surface of the rear lens in the second lens group,  $r_{5n}$  the curvature radius of the concave surface in the negative meniscus lens in the fifth lens group,  $r_{5p}$  the curvature radius of the convex surface opposed to the concave surface of the negative meniscus lens, in the positive lens placed adjacent to the concave surface of the negative meniscus lens in the fifth lens group,  $r_{4F}$  the first-object-side curvature radius in the rear lens placed closest to the second object in the fourth lens group,  $r_{4R}$  the second-object-side curvature radius in the rear lens placed closest to the second object in the fourth lens group,  $r_{5F}$  the first-object-side curvature radius in the second lens placed closest to the second object in the fifth lens group,  $r_{5R}$  the second-object-side curvature radius of the negative lens placed closest to the second object in the fifth lens group,  $r_{6F}$  the first-object-side curvature radius of the lens placed closest to the first object in the sixth lens group,  $d_{56}$  the lens group separation between the fifth lens group and the sixth lens group,  $d_6$  the axial distance from the lens surface closest to the first object in the sixth lens group to the second object, and  $\Phi$  the refracting power of the lens surface of the lens or lenses forming the sixth lens group.

(Table 1) First Embodiment

d0 = 105.33208

B = 1/5

NA = 0.55

Bf = 28.62263

L = 1200

15

20

25

30

35

40

45

50

55

	r	d	n
1	-821.91920	23.00000	1.50839
2	-391.93385	20.81278	
3	334.30413	20.00000	1.50839
4	239.01947	7.92536	
5	267.66514	28.00000	1.50839
6	-618.41676	1.04750	
7	337.90351	23.00000	1.50839
8	-1279.67000	0.97572	
9	200.03116	24.00000	1.50839
10	105.22457	22.04713	
11	219.65515	26.00000	1.50839
12	-546.12474	1.10686	
13	4788.40002	17.00000	1.50839
14	125.70412	20.76700	
15	-381.52610	12.90000	1.50839
16	134.36400	26.88549	
17	-127.38724	15.00000	1.50839

	18	433.13808	52.33906	
5	19	1260.83000	35.00000	1.50839
	20	-178.61526	14.91509	
10	21	-129.71674	22.80000	1.50839
	22	-202.88016	2.79782	
	23	-4128.12000	27.00000	1.50839
15	24	-299.28737	2.87255	
	25	556.52963	28.00000	1.50839
20	26	-928.16848	2.49780	
	27	367.82207	30.00000	1.50839
	28	-4438.51001	1.64701	
25	29	220.29374	31.00000	1.50839
	30	-1698.69000	3.60527	
30	31	4987.07001	21.00000	1.50839
	32	146.02635	11.76890	
	33	216.75649	17.00000	1.50839
35	34	161.01290	31.54706	
	35	-206.90673	15.90000	1.50839
40	36	309.12541	56.09046	
	37	-183.11187	18.00000	1.50839
	38	-894.17440	6.28784	
45	39	-409.02115	23.00000	1.50839
	40	-215.49999	1.14438	
50	41	3139.57999	23.00000	1.50839
	42	-320.84882	2.92283	
	43	445.47649	38.00000	1.50839

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	44	-348.37380	11.43498	
5	45	-229.01731	27.00000	1.50839
	46	-352.88961	1.10071	
10	47	370.91242	25.00000	1.50839
	48	-3446.41000	4.83032	
	49	178.35450	32.00000	1.50839
15	50	471.60399	3.29194	
	51	137.85195	39.90000	1.50839
20	52	331.09797	9.82671	
	53	520.77561	23.00000	1.50839
	54	80.26937	7.04896	
25	55	90.74309	71.00000	1.50839
	56	1836.49001		

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(Table 2) Values corresponding to the Conditions in the  
First Embodiment

$$(1) f_1 / f_3 = 1.47$$

$$(2) f_2 / f_4 = 1.31$$

$$(3) f_5 / L = 0.0988$$

$$(4) f_6 / L = 0.154$$

$$(5) f_n / f_2 = 0.589$$

$$(6) I / L = 2.33$$

$$(7) f_{24} / f_{23} = 0.990$$

$$(8) f_{22} / f_{23} = 1.31$$

$$(9) D / L = 0.0852$$

$$(10) f_4 / L = -0.0638$$

$$(11) f_2 / L = -0.0834$$

$$(12) (r_{5p} - r_{5n}) / (r_{5p} + r_{5n}) = 0.207$$

$$(13) (r_{4F} - r_{4R}) / (r_{4F} + r_{4R}) = -0.660$$

$$(14) (r_{5R} - r_{6F}) / (r_{5R} + r_{6F}) = -0.0613$$

$$(15) d_{56} / L = 0.00587$$

$$(16) d_6 / r_{6F} = 1.10$$

$$(17) (r_{5F} - r_{5R}) / (r_{5F} + r_{5R}) = 0.733$$

$$(18) 1 / (\phi_{21} \cdot L) = 0.895$$

$$(19) f_{21} / L = 0.260$$

$$(20) f_{2F} / f_{2R} = 0.604$$

(Table 3) Second Embodiment

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$$d_0 = 103.54346$$

$$B = 1/5$$

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$$N_A = 0.55$$

$$B_f = 29.06029$$

$$L = 1200$$

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	r	d	n
1	-2191.45999	23.00000	1.50839
2	-443.19378	18.81278	
3	372.47246	20.00000	1.50839
4	259.89086	7.92536	
5	296.05557	26.00000	1.50839
6	-527.24081	1.04750	
7	478.04893	27.00000	1.50839
8	-948.34609	0.97572	
9	210.20717	24.00000	1.50839
10	107.85292	24.04713	
11	214.18600	26.00000	1.50839
12	-438.52759	1.10686	
13	-1434.49001	17.00000	1.50839
14	132.17373	18.76700	
15	-370.22109	12.90000	1.50839
16	137.36441	26.88549	
17	-131.18161	15.00000	1.50839



	18	450.35044	53.03407	
5	19	1459.21001	35.00000	1.50839
	20	-182.99101	14.91509	
10	21	-132.88561	22.80000	1.50839
	22	-199.28914	2.79782	
	23	-5536.72998	27.00000	1.50839
15	24	-310.74563	2.87255	
	25	528.12523	28.00000	1.50839
20	26	-1200.55000	2.49780	
	27	320.15215	30.00000	1.50839
	28	-2820.19000	1.64701	
25	29	239.46093	31.00000	1.50839
	30	-2425.69000	5.60527	
30	31	$\infty$	21.00000	1.50839
	32	148.13116	9.76890	
	33	207.41773	17.00000	1.50839
35	34	155.42831	31.54706	
	35	-218.29971	15.90000	1.50839
40	36	304.21175	56.74759	
	37	-175.66635	18.00000	1.50839
	38	-1130.86000	6.28784	
45	39	-485.73656	23.00000	1.50839
	40	-216.43349	1.14438	
50	41	2806.14999	23.00000	1.50839
	42	-316.00620	2.92283	
55	43	437.43410	38.00000	1.50839

5	44	-355.32964	11.43498	
	45	-235.73758	27.00000	1.50839
	46	-360.50104	1.10071	
10	47	410.57953	25.00000	1.50839
	48	-3698.22000	4.83032	
	49	178.15299	32.00000	1.50839
15	50	506.53177	3.29194	
	51	137.46544	39.90000	1.50839
20	52	328.51597	9.82671	
	53	544.32105	23.00000	1.50839
	54	81.70638	7.04896	
25	55	92.81520	34.00000	1.50839
	56	511.57718	2.00000	
30	57	482.15006	35.00000	1.50839
	58	1631.30000		

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(Table 4) Values corresponding to the Conditions in the  
Second Embodiment

- (1)  $f_1 / f_3 = 1.50$
- (2)  $f_2 / f_4 = 1.39$
- (3)  $f_5 / L = 0.0971$
- (4)  $f_6 / L = 0.158$
- (5)  $f_n / f_2 = 0.568$
- (6)  $I / L = 2.21$
- (7)  $f_{24} / f_{23} = 1.01$
- (8)  $f_{22} / f_{23} = 1.21$
- (9)  $D / L = 0.0858$
- (10)  $f_4 / L = -0.0621$
- (11)  $f_2 / L = -0.0861$
- (12)  $(r_{5p} - r_{5n}) / (r_{5p} + r_{5n}) = 0.202$
- (13)  $(r_{4F} - r_{4R}) / (r_{4F} + r_{4R}) = -0.731$
- (14)  $(r_{5R} - r_{6F}) / (r_{5R} + r_{6F}) = -0.0637$
- (15)  $d_{56} / L = 0.00587$
- (16)  $d_6 / r_{6F} = 1.08$
- (17)  $(r_{5F} - r_{5R}) / (r_{5F} + r_{5R}) = 0.739$
- (18)  $1 / (\phi_{21} \cdot L) = 0.719$
- (19)  $f_{21} / L = 0.239$
- (20)  $f_{2F} / f_{2R} = 0.533$

(Table 5) Third Embodiment

5             $d_0 = 104.69561$

$B = 1/5$

$NA = 0.55$

10            $B_f = 29.13809$

$L = 1200$

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	r	d	n
20	1    1364.36000	23.00000	1.50839
	2    -612.17411	20.81278	
25	3    699.63988	24.00000	1.50839
	4    -301.81026	7.92536	
	5    -248.00150	20.00000	1.50839
30	6    -614.52792	1.04750	
	7    332.05244	27.00000	1.50839
	8    -582.52759	0.97572	
35	9    232.12759	24.00000	1.50839
	10   110.33434	27.04713	
40	11   230.79590	23.00000	1.50839
	12   -359.85171	1.10686	
	13   -1275.75999	17.00000	1.50839
45	14   127.98361	18.76700	
	15   -569.83204	12.90000	1.50839
50	16   140.20359	26.88549	
	17   -108.76770	15.00000	1.50839

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	18	593.61218	51.86789	
5	19	2324.85999	35.00000	1.50839
	20	-163.53564	14.91509	
10	21	-121.26603	22.80000	1.50839
	22	-192.12364	2.79782	
	23	-4480.40997	27.00000	1.50839
15	24	-297.83388	2.87255	
	25	445.50685	28.00000	1.50839
	26	-877.28296	2.49780	
20	27	422.96766	27.00000	1.50839
	28	-1570.03000	1.64701	
25	29	230.95785	31.00000	1.50839
	30	3000.00000	8.60527	
30	31	1800.00000	21.00000	1.50839
	32	138.38357	9.76890	
	33	191.56081	17.00000	1.50839
35	34	157.70119	31.54706	
	35	-217.22866	15.90000	1.50839
	36	294.71194	56.69427	
40	37	-173.19975	18.00000	1.50839
	38	-973.64548	6.28784	
45	39	-467.87775	23.00000	1.50839
	40	-215.12034	1.14438	
	41	2688.16000	23.00000	1.50839
50	42	-320.45010	2.92283	
	43	441.22198	40.00000	1.50839

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	44	-347.09282	9.43498	
5	45	-239.46132	27.00000	1.50839
	46	-386.98159	1.10071	
10	47	381.41679	28.00000	1.50839
	48	-2576.25000	4.83032	
	49	186.44642	29.00000	1.50839
15	50	570.80649	3.29194	
	51	138.75412	39.90000	1.50839
20	52	316.26440	9.82671	
	53	504.37073	23.00000	1.50839
	54	80.26770	7.04896	
25	55	91.17058	71.00000	1.50839
	56	1553.61000		

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(Table 6) Values corresponding to the Conditions in the  
Third Embodiment

$$(1) f_1 / f_3 = 1.46$$

$$(2) f_2 / f_4 = 1.27$$

$$(3) f_5 / L = 0.0977$$

$$(4) f_6 / L = 0.156$$

$$(5) f_n / f_2 = 0.591$$

$$(6) I / L = 2.93$$

$$(7) f_{24} / f_{23} = 0.816$$

$$(8) f_{22} / f_{23} = 1.04$$

$$(9) D / L = 0.0848$$

$$(10) f_4 / L = -0.0645$$

$$(11) f_2 / L = -0.0816$$

$$(12) (r_{5p} - r_{5n}) / (r_{5p} + r_{5n}) = 0.184$$

$$(13) (r_{4F} - r_{4R}) / (r_{4F} + r_{4R}) = -0.698$$

$$(14) (r_{5R} - r_{6F}) / (r_{5R} + r_{6F}) = -0.0636$$

$$(15) d_{56} / L = 0.00587$$

$$(16) d_6 / r_{6F} = 1.10$$

$$(17) (r_{5F} - r_{5R}) / (r_{5F} + r_{5R}) = 0.725$$

$$(18) 1 / (\phi_{21} \cdot L) = 0.590$$

$$(19) f_{21} / L = 0.234$$

$$(20) f_{2F} / f_{2R} = 0.611$$

(Table 7) Fourth Embodiment

d0 = 104.71662

B = 1/5

NA = 0.55

Bf = 28.76320

L = 1200

	r	d	n
1	955.26796	23.00000	1.50839
2	-675.53148	20.81278	
3	788.04209	24.00000	1.50839
4	-320.77870	7.92536	
5	-261.99847	20.00000	1.50839
6	-613.40707	1.04750	
7	343.77433	27.00000	1.50839
8	-614.74297	0.97572	
9	220.40014	24.00000	1.50839
10	111.87626	27.04713	
11	230.00000	23.00000	1.50839
12	-410.00000	1.10686	
13	-2449.05000	17.00000	1.50839
14	118.87129	18.76700	
15	-632.77988	12.90000	1.50839
16	143.15226	26.88549	
17	-108.88557	15.00000	1.50839



	18	595.22400	52.22565	
5	19	1526.21000	35.00000	1.50839
	20	-168.52598	14.91509	
10	21	-120.87196	22.80000	1.50839
	22	-188.10351	2.79782	
	23	-3191.22000	27.00000	1.50839
15	24	-296.62706	2.87255	
	25	697.45117	28.00000	1.50839
	26	-669.27158	2.49780	
20	27	358.82454	27.00000	1.50839
	28	-2986.21000	1.64701	
25	29	223.50971	31.00000	1.50839
	30	-1510.16000	8.60527	
30	31	-3596.81000	21.00000	1.50839
	32	141.11696	9.76890	
	33	194.35300	17.00000	1.50839
35	34	157.66411	31.54706	
	35	-209.96142	15.90000	1.50839
	36	307.10883	56.68624	
40	37	-175.13115	18.00000	1.50839
	38	-1162.95000	6.28784	
45	39	-505.38166	23.00000	1.50839
	40	-213.39177	1.14438	
50	41	3114.45000	23.00000	1.50839
	42	-339.03822	2.92283	
55	43	460.54759	40.00000	1.50839

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	44	-326.27369	9.43498	
5	45	-231.89968	27.00000	1.50839
	46	-372.57441	1.10071	
10	47	390.03678	28.00000	1.50839
	48	-1994.66000	4.83032	
	49	182.18377	29.00000	1.50839
15	50	525.45378	3.29194	
	51	138.67730	39.90000	1.50839
20	52	312.43609	9.82671	
	53	511.48346	23.00000	1.50839
	54	81.45867	7.04896	
25	55	93.64185	34.00000	1.50839
	56	934.34560	2.00000	
30	57	826.70065	35.00000	1.50839
	58	1680.21000	(Bf)	

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(Table 8) Values corresponding to the Conditions in the  
Fourth Embodiment

$$(1) f_1 / f_3 = 1.55$$

$$(2) f_2 / f_4 = 1.39$$

$$(3) f_5 / L = 0.0975$$

$$(4) f_6 / L = 0.158$$

$$(5) f_n / f_2 = 0.576$$

$$(6) I / L = 3.05$$

$$(7) f_{24} / f_{23} = 0.787$$

$$(8) f_{22} / f_{23} = 0.974$$

$$(9) D / L = 0.0851$$

$$(10) f_4 / L = -0.0606$$

$$(11) f_2 / L = -0.0843$$

$$(12) (r_{5p} - r_{5n}) / (r_{5p} + r_{5n}) = 0.169$$

$$(13) (r_{4F} - r_{4R}) / (r_{4F} + r_{4R}) = -0.738$$

$$(14) (r_{5R} - r_{6F}) / (r_{5R} + r_{6F}) = -0.0695$$

$$(15) d_{56} / L = 0.00587$$

$$(16) d_6 / r_{6F} = 1.07$$

$$(17) (r_{5F} - r_{5R}) / (r_{5F} + r_{5R}) = 0.725$$

$$(18) 1 / (\phi_{21} \cdot L) = 0.672$$

$$(19) f_{21} / L = 0.244$$

$$(20) f_{2F} / f_{2R} = 0.642$$

(Table 9) Fifth Embodiment

$$d_0 = 105.99385$$

$$B = 1/5$$

$$N_A = 0.55$$

$$B_f = 28.96856$$

$$L = 1200$$

	r	d	n
1	723.32335	28.00000	1.50839
2	-571.27029	2.00000	
3	-8470.94995	20.00000	1.50839
4	324.13159	7.92536	
5	360.44110	28.00000	1.50839
6	-432.97069	1.04750	
7	397.04484	27.00000	1.50839
8	-825.96923	0.97572	
9	214.74004	31.00000	1.50839
10	110.51892	24.04713	
11	229.41181	26.00000	1.50839
12	-396.52854	1.10686	
13	-1014.34000	17.00000	1.50839
14	137.90605	18.76700	
15	-418.55207	12.90000	1.50839
16	138.89479	26.88549	
17	-133.71351	15.00000	1.50839

	18	561.35918	52.53782	
5	19	1381.31000	35.00000	1.50839
	20	-188.69074	14.91509	
10	21	-134.03345	22.80000	1.50839
	22	-198.69180	2.79782	
	23	-3029.37000	27.00000	1.50839
15	24	-333.96362	2.87255	
	25	905.53484	28.00000	1.50839
20	26	-611.80005	2.49780	
	27	254.70879	30.00000	1.50839
	28	3936.53000	1.64701	
25	29	239.51669	31.00000	1.50839
	30	-1238.94000	5.60527	
30	31	-2379.42001	21.00000	1.50839
	32	150.43068	9.76890	
	33	209.21387	17.00000	1.50839
35	34	149.67785	31.54706	
	35	-199.55198	15.90000	1.50839
40	36	341.76300	57.70880	
	37	-170.75300	18.00000	1.50839
	38	-3700.60999	6.28784	
45	39	-1025.75000	23.00000	1.50839
	40	-212.37919	1.14438	
50	41	-3009.97000	23.00000	1.50839
	42	-312.33647	2.92283	
55	43	401.05778	37.00000	1.50839

5	44	-361.42967	12.43498	
	45	-231.63315	27.00000	1.50839
	46	-319.48896	1.10071	
10	47	355.64919	25.00000	1.50839
	48	3678.53000	4.83032	
	49	177.43364	32.00000	1.50839
15	50	553.83964	3.29194	
	51	137.68248	39.90000	1.50839
20	52	330.86342	9.82671	
	53	587.42747	23.00000	1.50839
	54	81.23164	7.04896	
25	55	93.74477	71.00000	1.50839
	56	1555.42999		

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(Table 10) Values corresponding to the Conditions in  
the Fifth Embodiment

$$(1) f_1 / f_3 = 1.58$$

$$(2) f_2 / f_4 = 1.63$$

$$(3) f_5 / L = 0.0923$$

$$(4) f_6 / L = 0.161$$

$$(5) f_n / f_2 = 0.554$$

$$(6) I / L = 2.27$$

$$(7) f_{24} / f_{23} = 1.04$$

$$(8) f_{22} / f_{23} = 1.17$$

$$(9) D / L = 0.0853$$

$$(10) f_4 / L = -0.0564$$

$$(11) f_2 / L = -0.0919$$

$$(12) (r_{5p} - r_{5n}) / (r_{5p} + r_{5n}) = 0.219$$

$$(13) (r_{4F} - r_{4R}) / (r_{4F} + r_{4R}) = -0.912$$

$$(14) (r_{5R} - r_{6F}) / (r_{5R} + r_{6F}) = -0.0715$$

$$(15) d_{56} / L = 0.00587$$

$$(16) d_6 / r_{6F} = 1.07$$

$$(17) (r_{5F} - r_{5R}) / (r_{5F} + r_{5R}) = 0.757$$

$$(18) 1 / (\phi_{21} \cdot L) = 0.650$$

$$(19) f_{21} / L = 0.242$$

$$(20) f_{2F} / f_{2R} = 0.541$$

(Table 11) Sixth Embodiment

$$d_0 = 105.91377$$

$$B = 1/5$$

$$NA = 0.55$$

$$Bf = 28.96856$$

$$L = 1200$$

	r	d	n
1	723.70616	28.00000	1.50839
2	-571.49375	1.98414	
3	-8427.42000	20.00000	1.50839
4	324.06902	8.06076	
5	360.49965	28.00000	1.50839
6	-432.97519	1.01484	
7	397.09644	27.00000	1.50839
8	-826.03537	0.88781	
9	214.74356	31.00000	1.50839
10	110.51666	24.03750	
11	229.41181	26.00000	1.50839
12	-396.60684	1.12963	
13	-1014.38000	17.00000	1.50839
14	137.92108	18.76756	
15	-418.59453	12.90000	1.50839
16	138.90550	26.88587	
17	-133.71351	15.00000	1.50839



	18	561.20342	52.51989	
5	19	1381.31000	35.00000	1.50839
	20	-188.68876	14.85490	
10	21	-134.03581	22.80000	1.50839
	22	-198.68592	2.89585	
	23	-3029.37000	27.00000	1.50839
15	24	-333.96362	2.88769	
	25	905.64444	28.00000	1.50839
20	26	-611.80428	2.47699	
	27	254.70879	30.00000	1.50839
	28	3936.53000	1.61920	
25	29	239.51669	31.00000	1.50839
	30	-1238.94000	5.60156	
30	31	-2379.42000	21.00000	1.50839
	32	150.42879	9.73510	
	33	209.20275	16.99160	1.50839
35	34	149.68297	31.54706	
	35	-199.55198	15.90229	1.50839
40	36	341.76300	57.70389	
	37	-170.75300	18.00000	1.50839
	38	-3700.61000	6.28293	
45	39	-1025.75000	23.00000	1.50839
	40	-212.37919	1.14438	
50	41	-3009.97000	23.00000	1.50839
	42	-312.33647	2.89661	
55	43	401.05778	37.00000	1.50839

	44	-361.42967	12.47918	
5	45	-231.65257	27.00000	1.50839
	46	-319.51171	1.23912	
10	47	355.64919	25.00000	1.50839
	48	3678.53000	4.82925	
	49	177.43453	32.00000	1.50839
15	50	553.98339	3.26768	
	51	137.68248	39.90000	1.50839
20	52	330.86342	9.82671	
	53	587.42747	23.00000	1.50839
	54	81.23164	7.04896	
25	55	93.74477	71.00000	1.50839
	56	1555.43000	(Bf)	

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(Table 12) Values corresponding to the Conditions in the Sixth Embodiment

$$(1) f_1 / f_3 = 1.58$$

$$(2) f_2 / f_4 = 1.63$$

$$(3) f_5 / L = 0.0924$$

$$(4) f_6 / L = 0.161$$

$$(5) f_n / f_2 = 0.554$$

$$(6) I / L = 2.25$$

$$(7) f_{24} / f_{23} = 1.04$$

$$(8) f_{22} / f_{23} = 1.17$$

$$(9) D / L = 0.0853$$

$$(10) f_4 / L = -0.0564$$

$$(11) f_2 / L = -0.0919$$

$$(12) (r_{5p} - r_{5n}) / (r_{5p} + r_{5n}) = 0.218$$

$$(13) (r_{4F} - r_{4R}) / (r_{4F} + r_{4R}) = -0.911$$

$$(14) (r_{5R} - r_{6F}) / (r_{5R} + r_{6F}) = -0.0715$$

$$(15) d_{56} / L = 0.00587$$

$$(16) d_6 / r_{6F} = 1.07$$

$$(17) (r_{5F} - r_{5R}) / (r_{5F} + r_{5R}) = 0.757$$

$$(18) 1 / (\phi_{21} \cdot L) = 0.650$$

$$(19) f_{21} / L = 0.242$$

$$(20) f_{2F} / f_{2R} = 0.541$$

In the above-described first embodiment,  $1/|\Phi_L| = 0.149$  for the object-side lens surface of the positive lens  $L_{61}$ , thus satisfying the condition (21). In the second embodiment,  $1/|\Phi_L| = 0.152$  for the object-side lens surface of the positive lens  $L_{61}$  and  $1/|\Phi_L| = 0.709$  for the object-side lens surface of the positive lens  $L_{62}$ , thus satisfying the condition (21). In the third embodiment,  $1/|\Phi_L| = 0.149$  for the object-side lens surface of the positive lens  $L_{61}$ , thus satisfying the condition (21). In the fourth embodiment,  $1/|\Phi_L| = 0.153$  for the object-side lens surface of the positive lens  $L_{61}$  and  $1/|\Phi_L| = 1.36$  for the object-side lens surface of the positive lens  $L_{62}$ , thus satisfying the condition (21). In the fifth embodiment,  $1/|\Phi_L| = 0.153$  for the object-side lens surface of the positive lens  $L_{61}$ , thus satisfying the condition (21). In the sixth embodiment,  $1/|\Phi_L| = 0.154$  for the object-side lens surface of the positive lens  $L_{61}$ , thus satisfying the condition (21). Therefore, the sixth lens group  $G_6$  in each embodiment is composed of three or less lenses having the lens surface(s) satisfying the condition (21).

From the above values of specifications for the respective embodiments, it is understood that the telecentricity is achieved on the object side (on the reticle side) and on the image side (on the wafer side) while maintaining a relatively wide exposure area and a large numerical aperture in each embodiment.

Fig. 9, Fig. 10, Fig. 11, Fig. 12, Fig. 13, and Fig. 14 show aberration diagrams of various aberrations in the first to the sixth embodiments according to the present invention.

Here, in each aberration diagram, NA represents the numerical aperture of the projection optical system and Y the image height. In each aberration diagram of astigmatism, the dotted line represents a meridional image surface (meridional image surface) and the solid line a sagittal image surface (sagittal image surface).

From comparison of the aberration diagrams, it is seen that the various aberrations are corrected in a good balance in each embodiment, particularly the distortion is corrected very well over the entire image up to a nearly zero state and the high-resolving-power projection optical system is achieved with a large numerical aperture.

Although the above embodiments showed the examples where the excimer laser for supplying the light of 248.4 nm was used as a light source, it is needless to mention that, without a need to be limited to the examples, the present invention can be applied to systems using extreme ultraviolet light sources such as an excimer laser for supplying the light of 193 nm, mercury arc lamps for supplying the light of the g-line (436 nm) or the i-line (365 nm), or light sources for supplying the light in the ultraviolet region other than those.

In the embodiments neither of the lenses constituting the projection optical system is a compound lens, and either of them is made of a single optical material, i.e., of quartz ( $\text{SiO}_2$ ). Here, a cost reduction can be achieved because a single optical material forms each lens in the above embodiments. However, if the exposure light has a certain half width, a chromatic aberration can be corrected by a combination of quartz ( $\text{SiO}_2$ ) and fluorite ( $\text{CaF}_2$ ) or by a combination of other optical materials. Further, if the exposure light source supplies the exposure light in a wide band, the chromatic aberration can be corrected by a combination of plural types of optical materials.

As described above, the exposure apparatus relating to the present invention has achieved the projection optical systems which are bitelecentric optical systems with a relatively wide exposure area kept and which are high-resolving-power projection optical systems in which the various aberrations are corrected in a good balance and which have a large numerical aperture. Particularly, the distortion is corrected very well in the projection optical systems of the present invention. Accordingly, the present invention can enjoy an extreme reduction of image stress, because the distortion is also corrected very well in addition to the achievement of the bitelecentricity.

From the invention thus described, it will be obvious that the invention may be varied in many ways. Such variations are not to be regarded as a departure from the spirit and scope of the invention, and all such modifications as would be obvious to one skilled in the art are intended to be included within the scope of the following claims.

The basic Japanese Application No. 6-311050 (311050/1994) filed on December 14, 1994 is hereby incorporated by reference.

## Claims

1. A projection optical system located between a first and second objects, for projecting an image of the first object onto the second object, said projection optical system having:

a first lens group with positive refracting power, said first lens group being placed between the first and second objects;

a second lens group with negative refracting power, said second lens group being placed between said first lens group and the second object;

a third lens group with positive refracting power, said third lens group being placed between said second lens group and the second object;

a fourth lens group with negative refracting power, said fourth lens group being placed between said third lens group and the second object;

a fifth lens group with positive refracting power, said fifth lens group being placed between said fourth lens group and the second object; and

a sixth lens group with positive refracting power, said sixth lens group being placed between said fifth lens group and the second object.

2. A projection optical system according to claim 1, wherein said first lens group includes at least two positive lenses, said third lens group includes at least three positive lenses, said fourth lens group includes at least three negative lenses, said fifth lens group includes at least five positive lenses and at least one negative lens, and said sixth lens group includes at least one positive lens.

3. A projection optical system according to claim 1, wherein said second lens group comprises a front lens placed as closest to the first object and having negative refracting power with a concave surface to the second object, a rear lens placed as closest to the second object and having negative refracting power with a concave surface to the first

object, and an intermediate lens group placed between said front and rear lenses in said second lens group, and wherein said intermediate lens group has a first lens with positive refracting power, a second lens with negative refracting power, a third lens with negative refracting power, and a fourth lens with negative refracting power in the named order from the side of the first object.

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4. A projection optical system according to claim 3, wherein the first lens with positive refracting power in said intermediate lens group in said second lens group has a lens shape with a convex surface to the second object.

5. A projection optical system according to claim 2, wherein said fourth lens group comprises a front lens placed as closest to the first object and having negative refracting power with a concave surface to the second object, a rear lens placed as closest to the second object and having negative refracting power with a concave surface to the first object, and at least one negative lens placed between said front lens in said fourth lens group and said rear lens in said fourth lens group.

6. A projection optical system according to claim 1, wherein said fifth lens group comprises a negative meniscus lens, and a positive lens placed as adjacent to a concave surface of said negative meniscus lens and having a convex surface opposed to the concave surface of said negative meniscus lens.

7. A projection optical system according to claim 6, wherein said negative meniscus lens and said positive lens adjacent to the concave surface of said negative meniscus lens are placed between at least one positive lens in said fifth lens group and at least one positive lens in said fifth lens group.

8. A projection optical system according to claim 1, wherein said fifth lens group comprises a negative lens placed as closest to the second object and having a concave surface opposed to the second object.

9. A projection optical system according to claim 8, wherein said sixth lens group comprises a lens placed as closest to the first object and having a convex surface opposed to the first object.

10. A projection optical system located between a first and second object, for projecting an image of the first object onto the second object, said projection optical system having a first lens group with positive refracting power, a second lens group, a third lens group with positive refracting power, a fourth lens group with negative refracting power, a fifth lens group with positive refracting power, and a sixth lens group with positive refracting power in the named order from the side of the first object,

wherein said second lens group comprises a front lens placed as closest to the first object and having negative refracting power with a concave surface to the second object, a rear lens placed as closest to the second object and having negative refracting power with a concave surface to the first object, and an intermediate lens group placed between said front and rear lenses in said second lens group,

wherein said intermediate lens group has a first lens with positive refracting power, a second lens with negative refracting power, a third lens with negative refracting power, and a fourth lens with negative refracting power in the named order from the side of the first object, and

wherein the following conditions are satisfied when a focal length of said first lens group is  $f_1$ , a focal length of said second lens group is  $f_2$ , a focal length of said third lens group is  $f_3$ , a focal length of said fourth lens group is  $f_4$ , a focal length of said fifth lens group is  $f_5$ , a focal length of said sixth lens group is  $f_6$ , an overall focal length of said second lens to said fourth lens in said intermediate lens group in said second lens group is  $f_n$ , and a distance from the first object to the second object is L:

$$0.1 < f_1/f_3 < 17$$

$$0.1 < f_2/f_4 < 14$$

$$0.01 < f_5/L < 0.9$$

$$0.02 < f_6/L < 1.6$$

$$0.01 < f_n/f_2 < 2.0.$$

11. A projection optical system according to claim 10, wherein the following condition is satisfied when an axial distance from the first object to a first-object-side focal point of the whole of said projection optical system is I and the distance from the first object to the second object is L:

$$1.0 < f/L.$$

12. A projection optical system according to claim 10, wherein said first lens group includes at least two positive lenses, said third lens group includes at least three positive lenses, said fourth lens group includes at least three negative lenses, said fifth lens group includes at least five positive lenses and at least one negative lens, and said sixth lens group includes at least one positive lens.

13. A projection optical system according to claims 10, wherein said intermediate lens group in said second lens group has negative refracting power.

14. A projection optical system according to claims 10, wherein the following condition is satisfied when the focal length of said second lens group is  $f_2$  and the distance from the first object to the second object is L:

$$-0.8 < f_2/L < -0.050.$$

15. A projection optical system according to claims 10, wherein the following condition is satisfied when a focal length of said front lens placed as closest to the first object in said second lens group and having negative refracting power with a concave surface to the second object is  $f_{2F}$  and a focal length of said rear lens placed as closest to the second object in said second lens group and having negative refracting power with a concave surface to the first object is  $f_{2R}$ :

$$0 \leq f_{2F}/f_{2R} < 18.$$

16. A projection optical system according to claim 10, wherein the following condition is satisfied when a focal length of said third lens with negative refracting power in said second lens group is  $f_{23}$  and a focal length of said fourth lens with negative refracting power in said intermediate lens group in said second lens group is  $f_{24}$ :

$$0.07 < f_{24}/f_{23} < 7.$$

17. A projection optical system according to claim 10, wherein the following condition is satisfied when a focal length of said second lens with negative refracting power in said intermediate lens group in said second lens group is  $f_{22}$  and a focal length of said third lens with negative refracting power in said intermediate lens group in said second lens group is  $f_{23}$ :

$$0.1 < f_{22}/f_{23} < 10.$$

18. A projection optical system according to claim 10, wherein the following condition is satisfied when an axial distance from a second-object-side lens surface of said fourth lens with negative refracting power in said intermediate lens group in said second lens group to a first-object-side lens surface of said rear lens in said second lens group is D and the distance from the first object to the second object is L:

$$0.05 < D/L < 0.4.$$

19. A projection optical system according to claim 10, wherein said first lens with positive refracting power in said intermediate lens group in said second lens group has a lens shape with a convex surface to the second object, and wherein the following condition is satisfied when the refracting power of a second-object-side lens surface of said first lens with positive refracting power in said intermediate lens group in said second lens group is  $\Phi_{21}$  and the distance from the first object to the second object is L:

$$0.54 < 1/(\Phi_{21} \cdot L) < 10.$$

20. A projection optical system according to claim 10, wherein the following condition is satisfied when a focal length of said first lens with positive refracting power in said intermediate lens group in said second lens group is  $f_{21}$  and the distance from the first object to the second object is L:

$$0.230 < f_{21}/L < 0.40.$$

21. A projection optical system according to claim 10, wherein the following condition is satisfied when the focal length of said fourth lens group is  $f_4$  and the distance from said the first object to the second object is L:

$$-0.098 < f_4/L < -0.005.$$

22. A projection optical system according to claim 10, wherein said fourth lens group comprises a front lens placed as closest to the first object and having negative refracting power with a concave surface to the second object, a rear lens placed as closest to the second object and having negative refracting power with a concave surface to the first object, and at least one negative lens placed between said front lens in said fourth lens group and said rear lens in said fourth lens group, and

wherein the following condition is satisfied when a radius of curvature on the first object side in said rear lens placed as closest to the second object in said fourth lens group is  $r_{4F}$  and a radius of curvature on the second object side in said rear lens placed as closest to the second object in said fourth lens group is  $r_{4R}$ :

$$-1.00 \leq (r_{4F} - r_{4R})/(r_{4F} + r_{4R}) < 0.$$

23. A projection optical system according to claim 10, wherein said fifth lens group comprises a negative meniscus lens, and a positive lens placed as adjacent to a concave surface of said negative meniscus lens and having a convex surface opposed to the concave surface of said negative meniscus lens, and

wherein the following condition is satisfied when a radius of curvature of the concave surface of said negative meniscus lens in said fifth lens group is  $r_{5n}$  and a radius of curvature of the convex surface opposed to the concave surface of said negative meniscus lens in said positive lens placed adjacent to the concave surface of said negative meniscus lens in said fifth lens group is  $r_{5p}$ :

$$0 < (r_{5p} - r_{5n})/(r_{5p} + r_{5n}) < 1.$$

24. A projection optical system according to claim 23, wherein said negative meniscus lens and said positive lens adjacent to the concave surface of said negative meniscus lens are placed between at least one positive lens in said fifth lens group and at least one positive lens in said fifth lens group.

25. A projection optical system according to claim 10, wherein said fifth lens group comprises a negative lens placed as closest to the second object and having a concave surface opposed to the second object, and

wherein the following condition is satisfied when a radius of curvature on the first object side in said negative lens closest to the second object in said fifth lens group is  $r_{5F}$  and a radius of curvature on the second object side in said negative lens closest to the second object in said fifth lens group is  $r_{5R}$ :

$$0.30 < (r_{5F} - r_{5R})/(r_{5F} + r_{5R}) < 1.28.$$

26. A projection optical system according to claim 10, wherein said fifth lens group comprises a negative lens placed as closest to the second object and having a concave surface opposed to the second object and said sixth lens group comprises a lens placed as closest to the first object and having a convex surface opposed to the first object, and

wherein the following condition is satisfied when a radius of curvature on the second object side, of said negative lens placed as closest to the second object in said fifth lens group is  $r_{5R}$  and a radius of curvature on the first object side, of said lens placed as closest to the first object in said sixth lens group is  $r_{6F}$ :

$$-0.90 < (r_{5R} - r_{6F})/(r_{5R} + r_{6F}) < -0.001.$$

27. A projection optical system according to claim 10, wherein the following condition is satisfied when a lens group separation between said fifth lens group and said sixth lens group is  $d_{56}$  and the distance from the first object to the second object is  $L$ :

$$d_{56}/L < 0.017.$$

28. A projection optical system according to claim 10, wherein the following condition is satisfied when a radius of curvature of a lens surface closest to the first object in said sixth lens group is  $r_{6F}$  and an axial distance from the lens surface closest to the first object in said sixth lens group to the second object is  $d_6$ :

$$0.50 < d_6/r_{6F} < 1.50.$$

29. A projection optical system according to claim 10, wherein said sixth lens group comprises three or less lenses having at least one surface satisfying the following condition:

$$1/|\Phi L| < 20.$$

where  $\Phi$ : refracting power of the lens surface;

L: object-image distance from the first object to the second object.

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30. A projection optical system according to claims 10, wherein a magnification of said projection optical system is 5:1.

31. An exposure apparatus comprising:

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a stage allowing a photosensitive substrate to be held on a main surface thereof;

an illumination optical system for emitting exposure light of a predetermined wavelength and transferring a predetermined pattern on a mask onto the substrate; and

a projecting optical system for projecting an image of the mask, on the substrate surface, said projecting optical system having:

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a first lens group with positive refracting power, said first lens group being placed between the mask and the main surface of said stage;

a second lens group with negative refracting power, said second lens group being placed between said first lens group and the main surface of said stage;

a third lens group with positive refracting power, said third lens group being placed between said second lens group and the main surface of said stage;

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a fourth lens group with negative refracting power, said fourth lens group being placed between said third lens group and the main surface of said stage;

a fifth lens group with positive refracting power, said fifth lens group being placed between said fourth lens group and the main surface of said stage; and

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a sixth lens group with positive refracting power, said sixth lens group being placed between said fifth lens group and the main surface of said stage.

32. An exposure apparatus according to claim 31, wherein said second lens group comprises a front lens placed as closest to the first object and having negative refracting power with a concave surface to the second object, a rear lens placed as closest to the second object and having negative refracting power with a concave surface to the first object, and an intermediate lens group placed between said front and rear lenses in said second lens group,

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wherein said intermediate lens group has a first lens with positive refracting power, a second lens with negative refracting power, a third lens with negative refracting power, and a fourth lens with negative refracting power in the named order from the side of the first object, and

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wherein the following conditions are satisfied when a focal length of said first lens group is  $f_1$ , a focal length of said second lens group is  $f_2$ , a focal length of said third lens group is  $f_3$ , a focal length of said fourth lens group is  $f_4$ , a focal length of said fifth lens group is  $f_5$ , a focal length of said sixth lens group is  $f_6$ , an overall focal length of said second lens to said fourth lens in said intermediate lens group in said second lens group is  $f_n$ , and a distance from the first object to the second object is L:

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$$0.1 < f_1/f_3 < 17$$

$$0.1 < f_2/f_4 < 14$$

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$$0.01 < f_5/L < 0.9$$

$$0.02 < f_6/L < 1.6$$

$$0.01 < f_n/f_2 < 2.0.$$

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Fig. 1

F: FIRST OBJECT SIDE  
FOCAL POINT

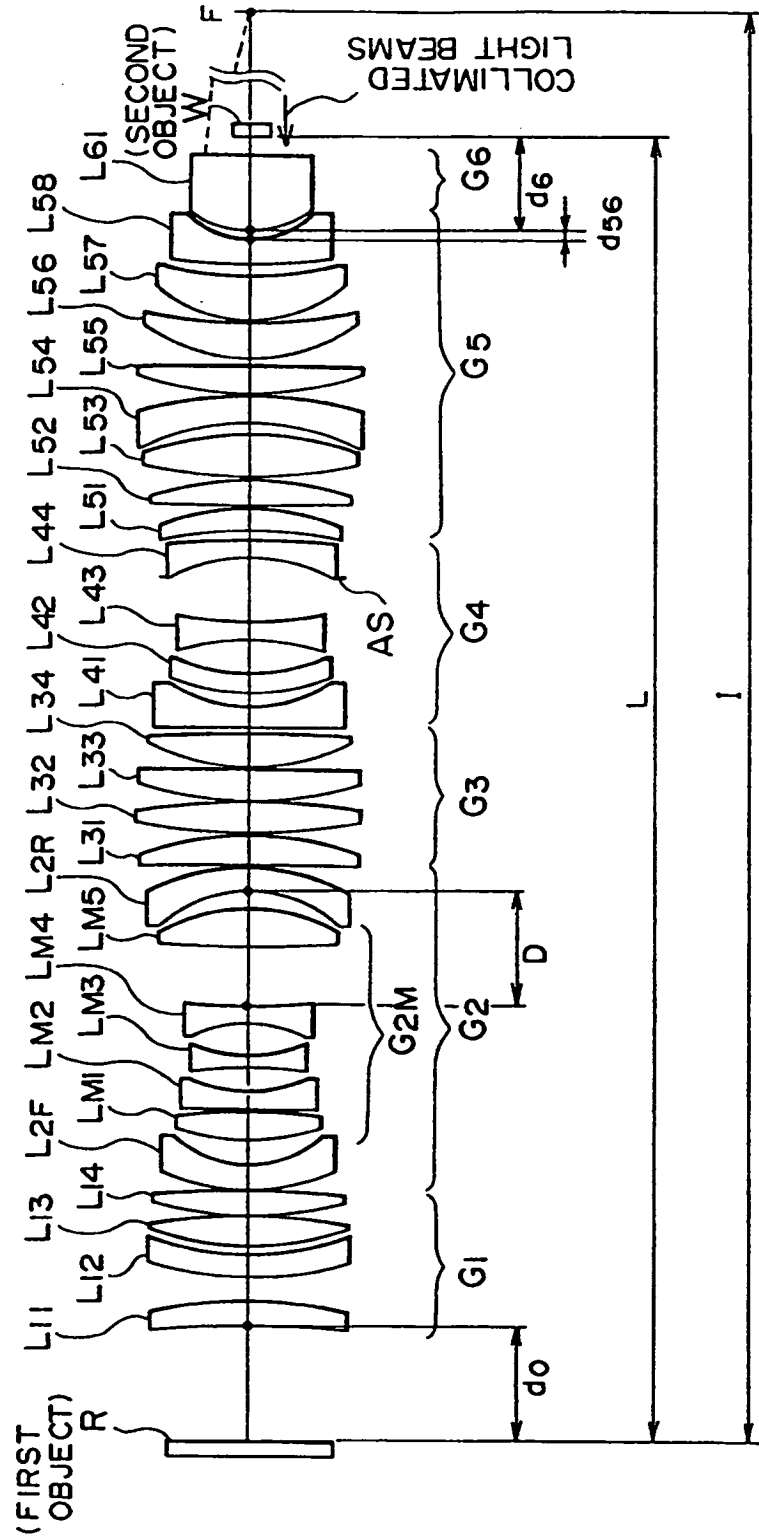


Fig. 2

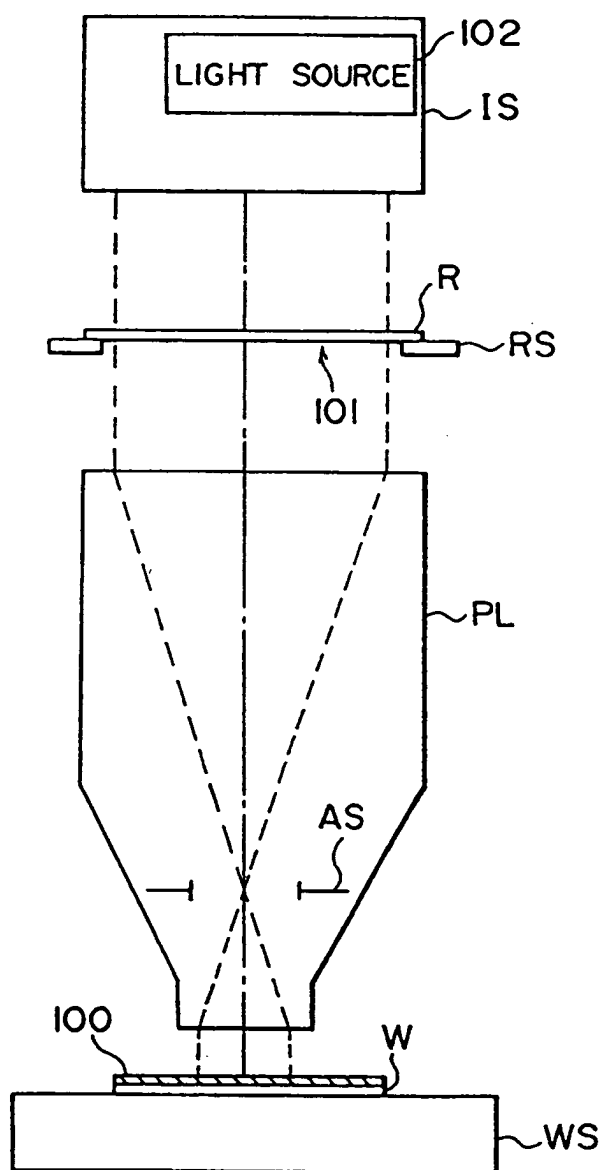


Fig. 3

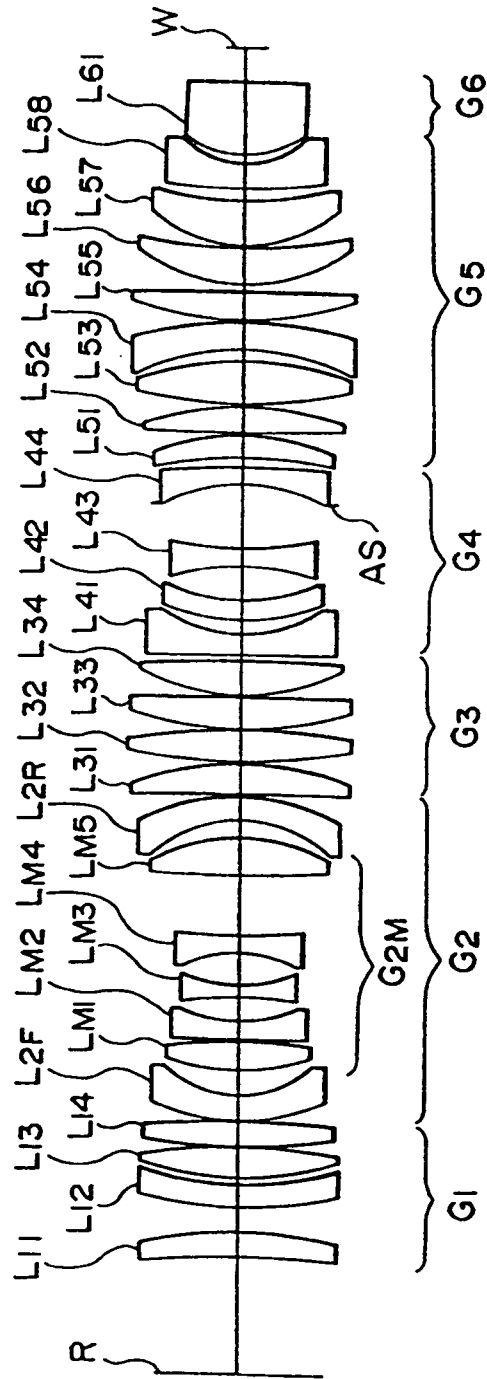


Fig. 4

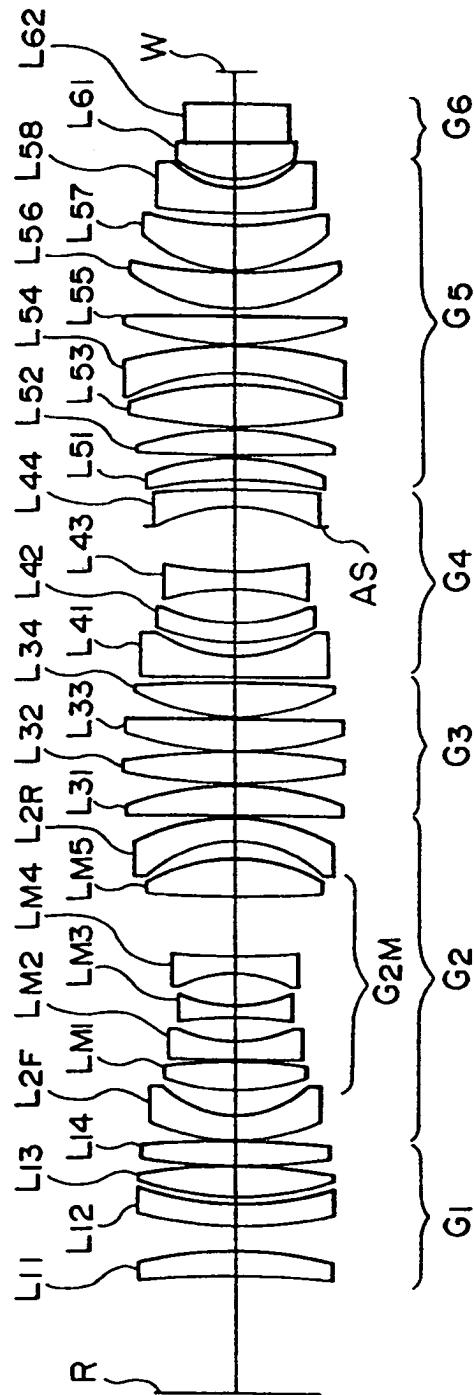
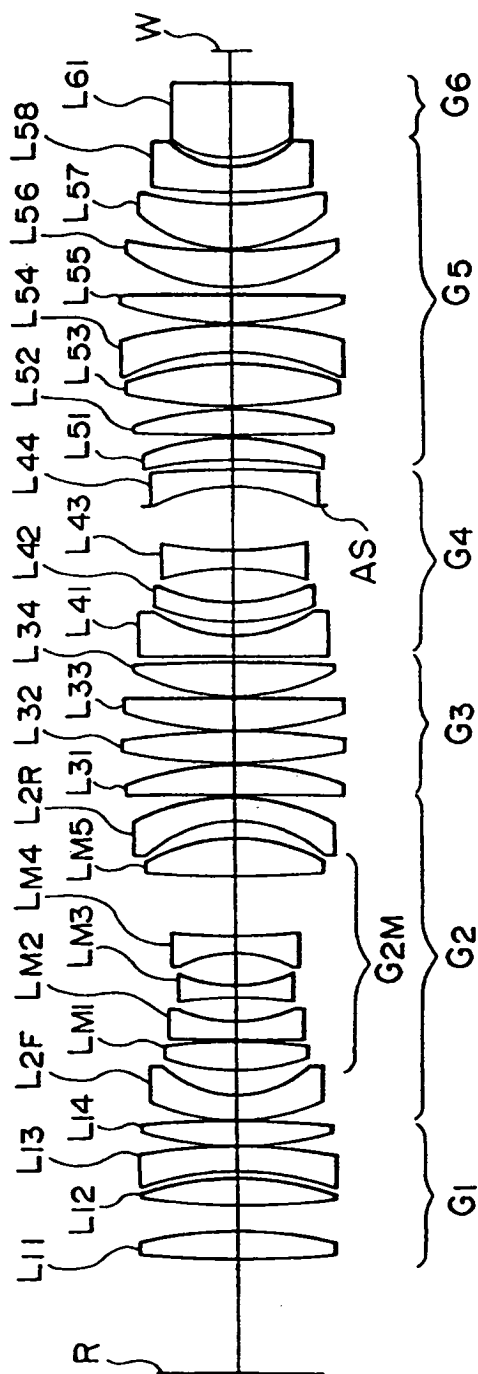


Fig. 5.



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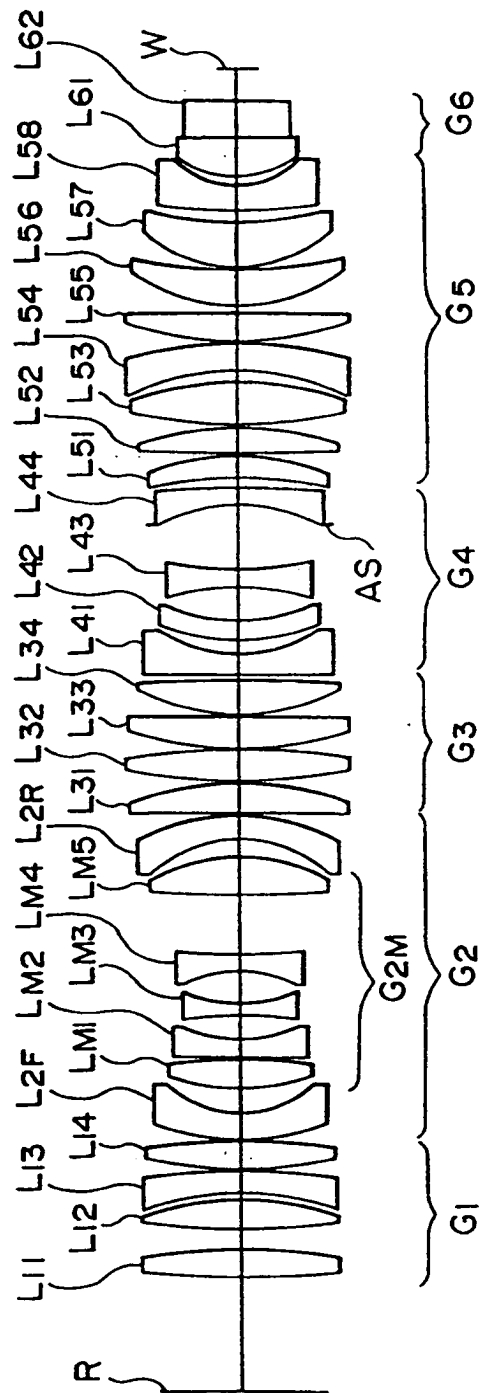


Fig. 7

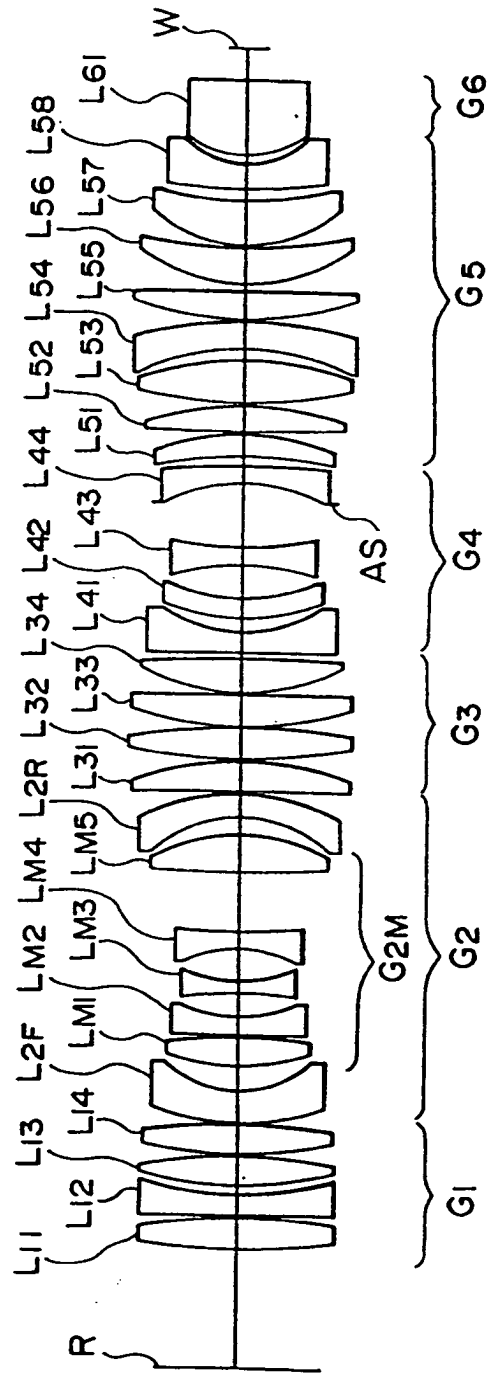


Fig. 8

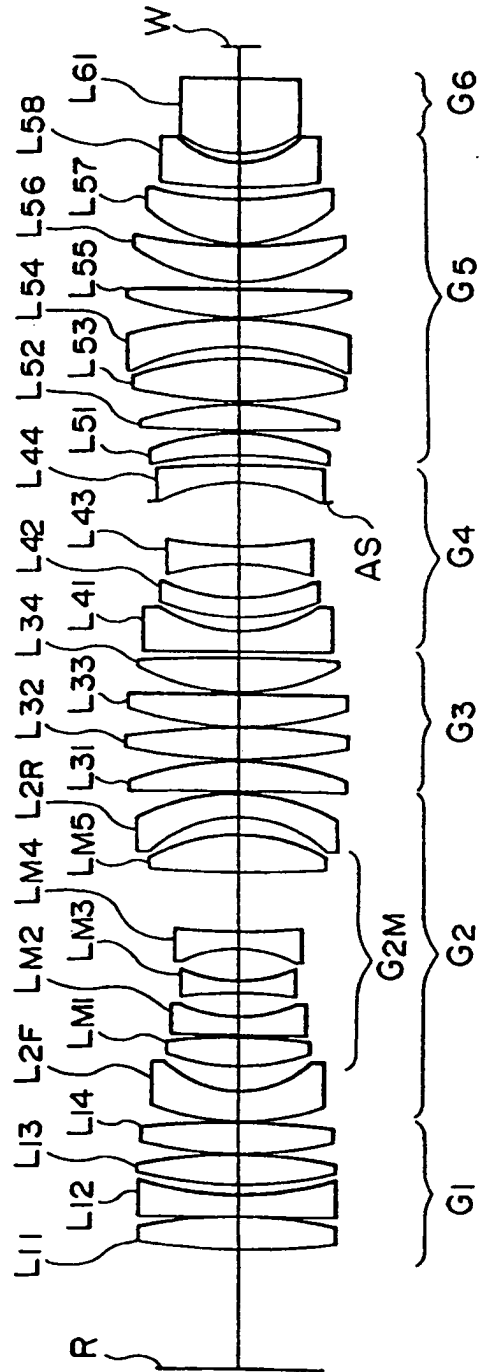




Fig. 9

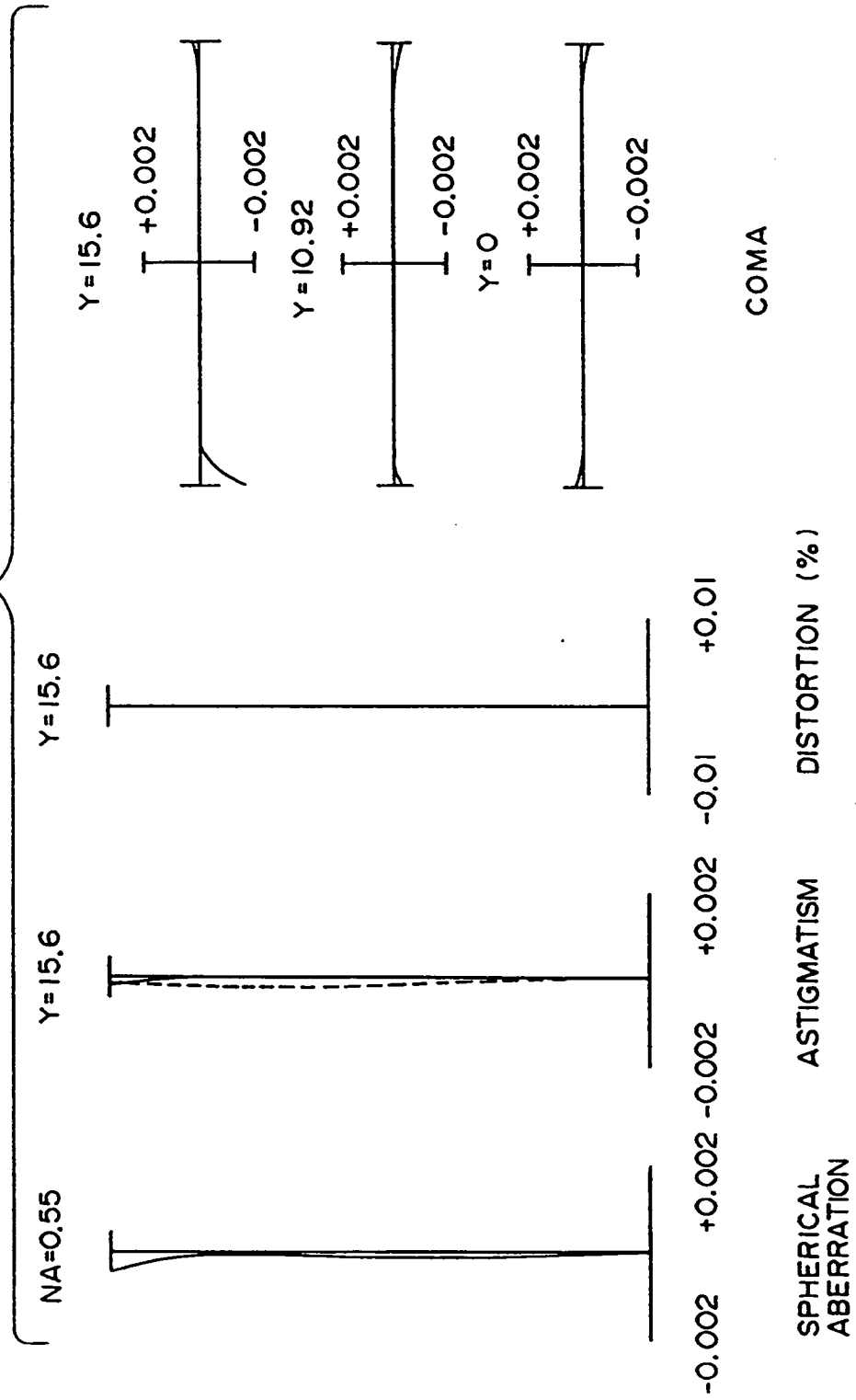


Fig. 10

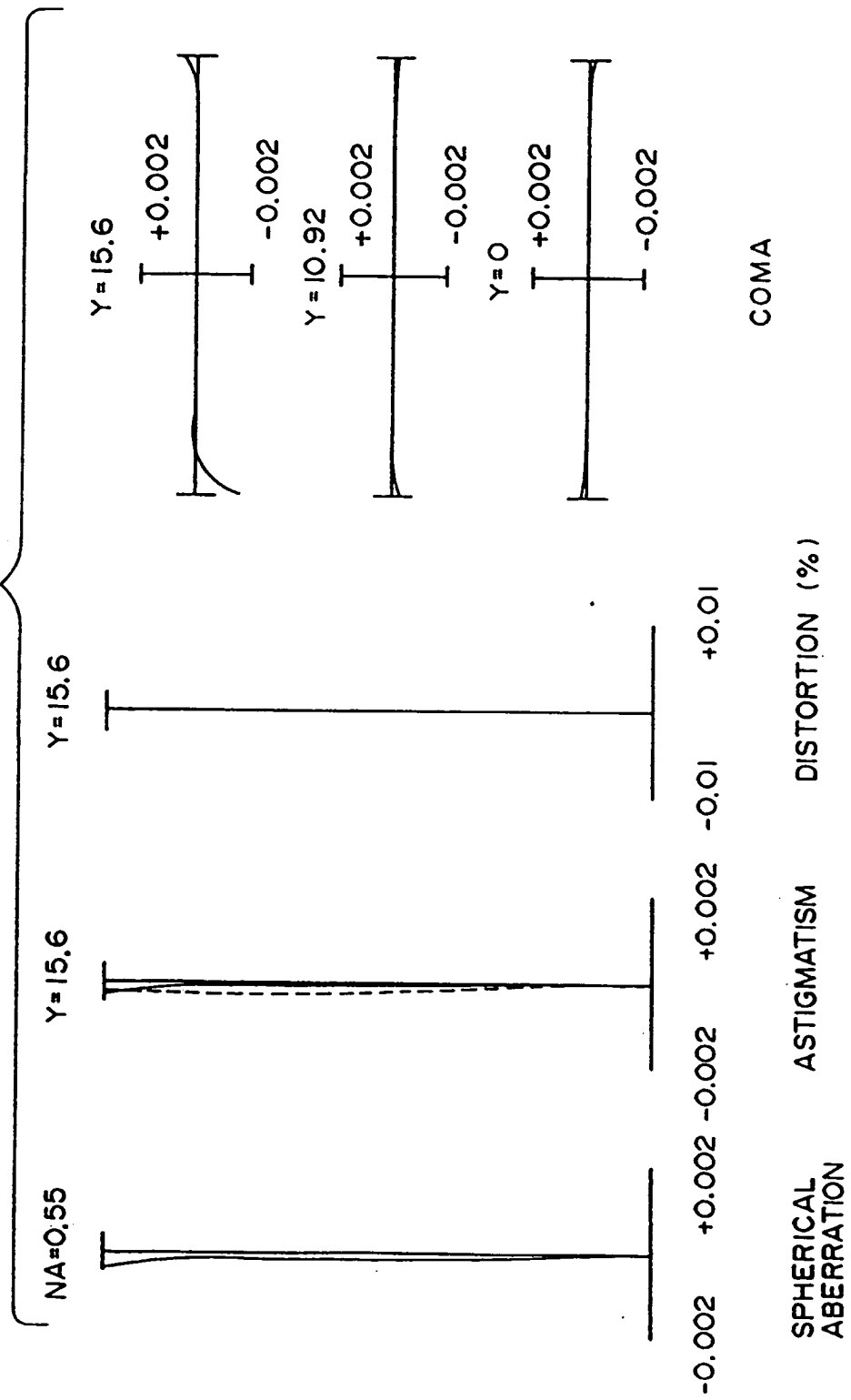


Fig. 11

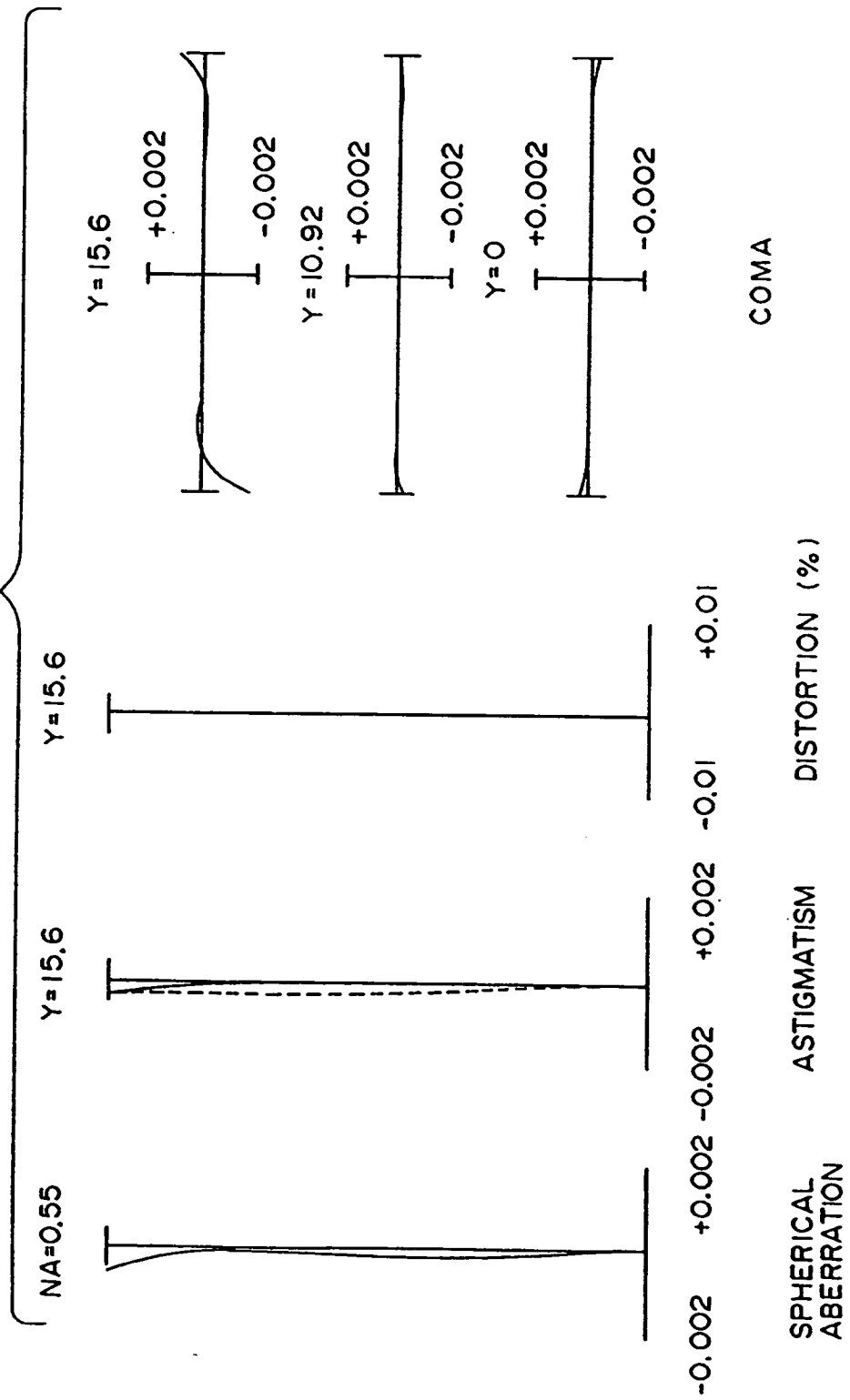


Fig. 12

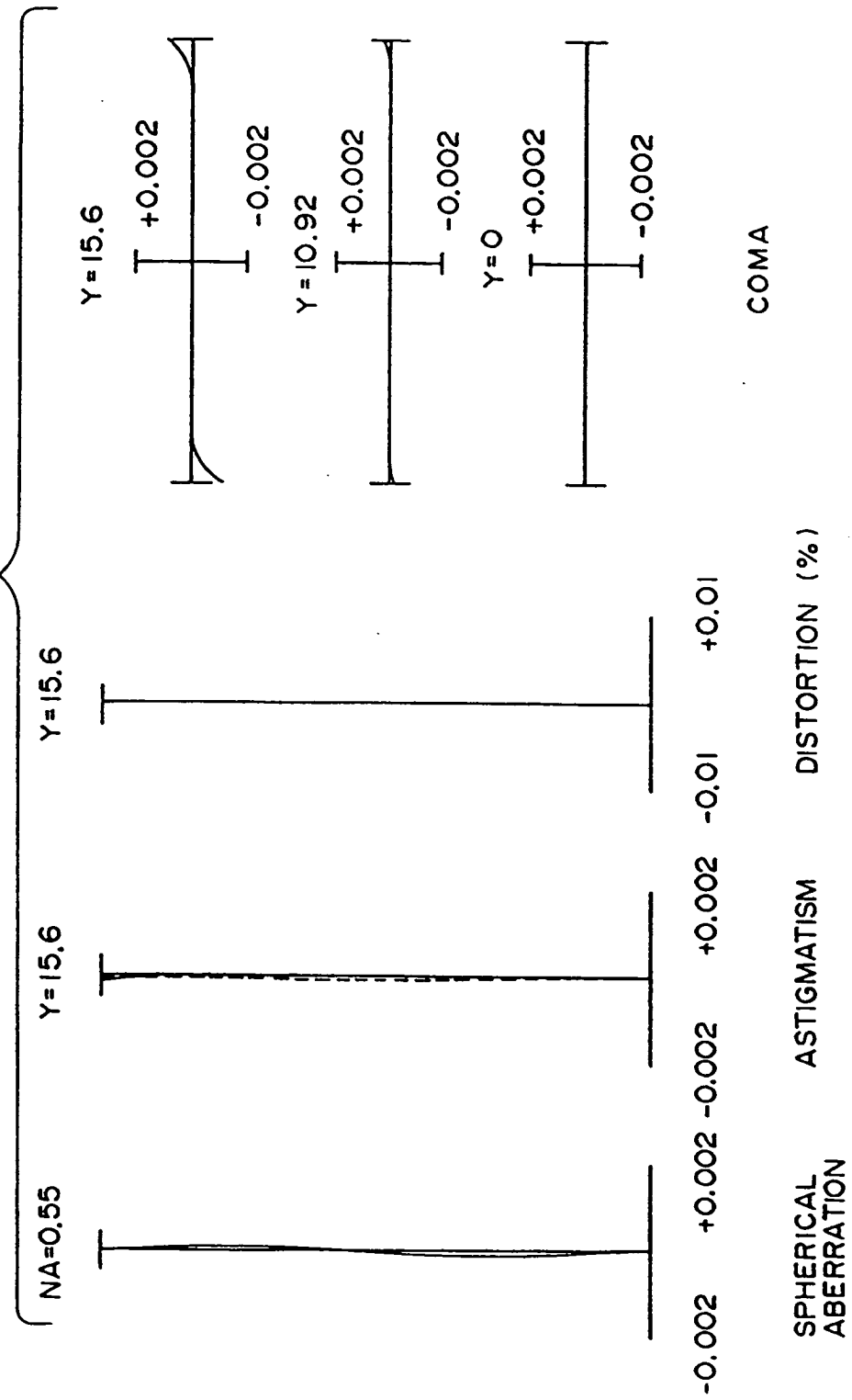


Fig. 13

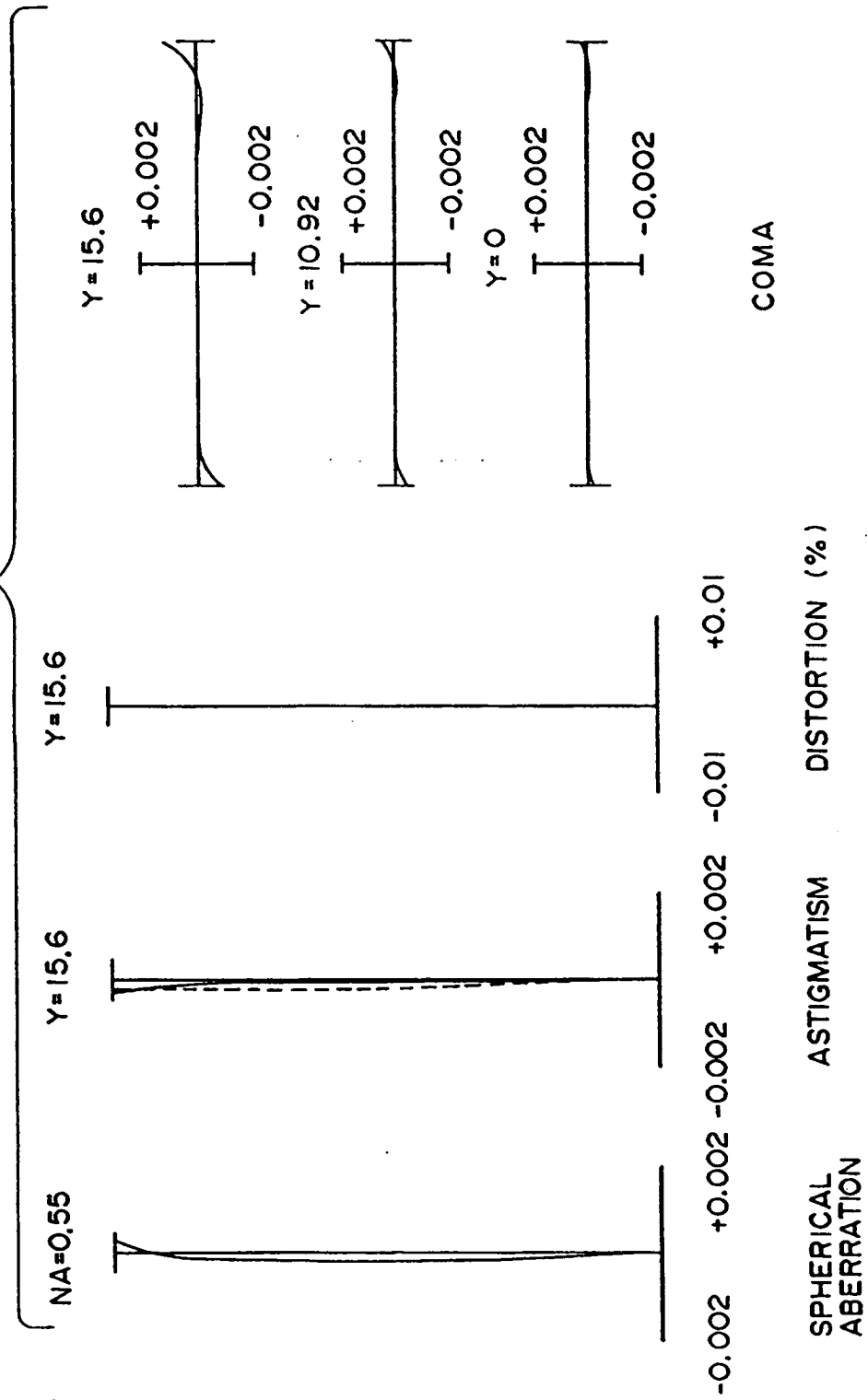
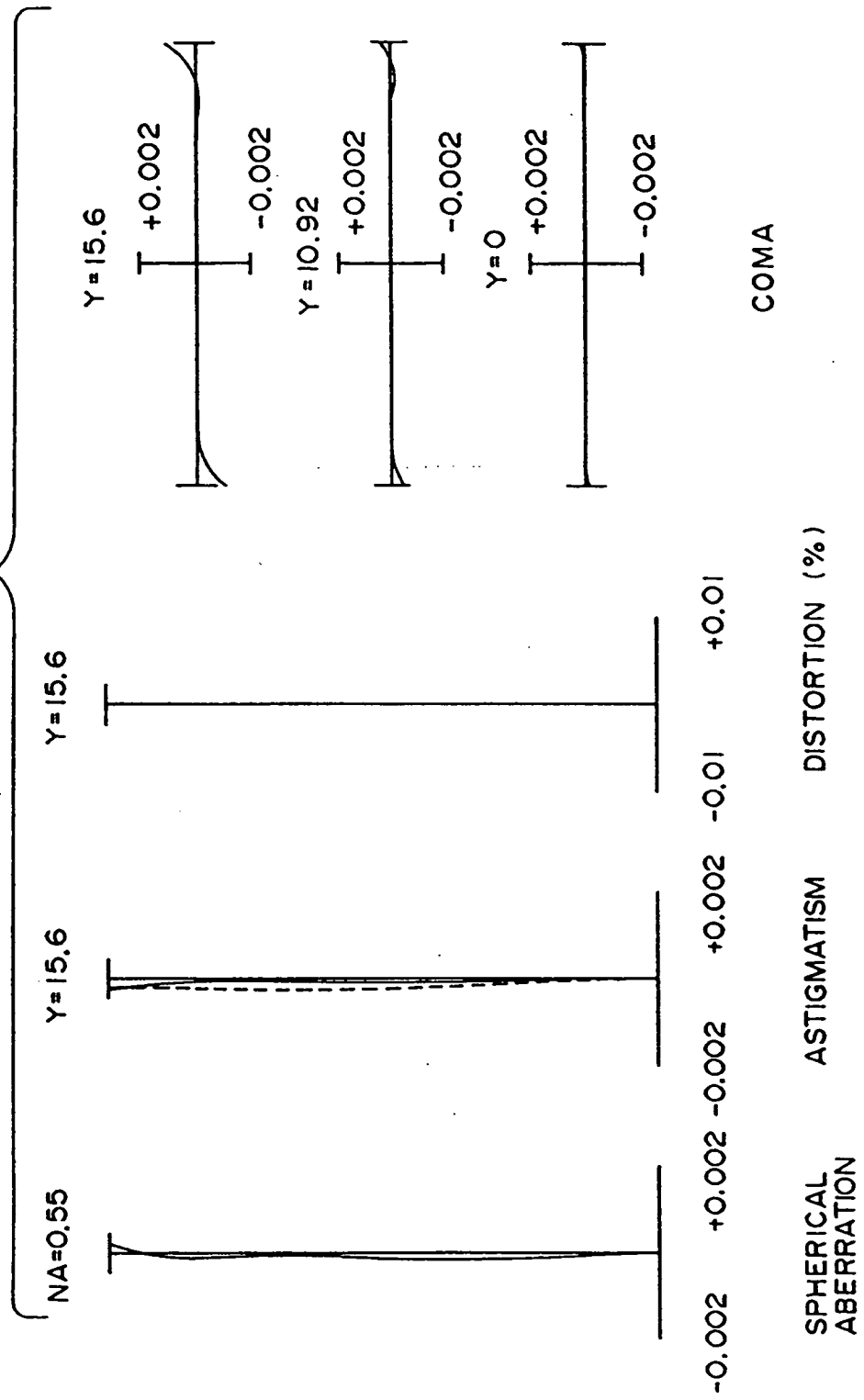


Fig. 14





European Patent  
Office

# EUROPEAN SEARCH REPORT

Application Number  
EP 95 10 1619

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
A	US-A-5 159 496 (KATAOKA) * the whole document *	1,10,31	G02B13/24 G02B9/62 G02B13/14 G03F7/20
A	US-A-3 737 215 (DE JAGER) * the whole document *	1,10,31	
A	US-A-4 080 048 (KIMURA) * the whole document *	1,10,31	
A	WO-A-93 04391 (EASTMAN KODAK) * the whole document *	1,10,31	
A	US-A-3 955 883 (SUGIYAMA) * the whole document *	1,10,31	
A	PATENT ABSTRACTS OF JAPAN vol. 7, no. 73 (P-186) 25 March 1983 & JP-A-58 004 112 (OLYMPUS) * abstract; figure *	1,10,31	
D,A	US-A-5 260 832 (TOGINO ET AL) * the whole document *	1,10,31	TECHNICAL FIELDS SEARCHED (Int.Cl.6)
D,A	PATENT ABSTRACTS OF JAPAN vol. 17, no. 586 (P-1633) 26 October 1993 & JP-A-05 173 065 (OLYMPUS) 13 July 1993 * abstract; figure *	1,10,31	G02B G03F
D,A	PATENT ABSTRACTS OF JAPAN vol. 12, no. 366 (P-765) 30 September 1988 & JP-A-63 118 115 (SIGMA) 23 May 1988 * abstract; figure *	1,10,31	
The present search report has been drawn up for all claims			
Place of search <b>THE HAGUE</b>		Date of completion of the search <b>4 April 1995</b>	Examiner <b>Ward, S</b>
<b>CATEGORY OF CITED DOCUMENTS</b> X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document		T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document	

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